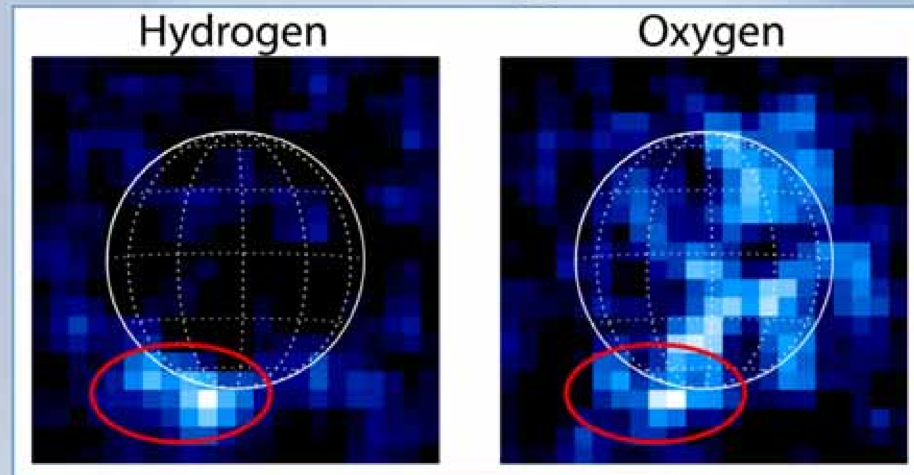
Review of Europa Datasets with Potential Plume Evidence

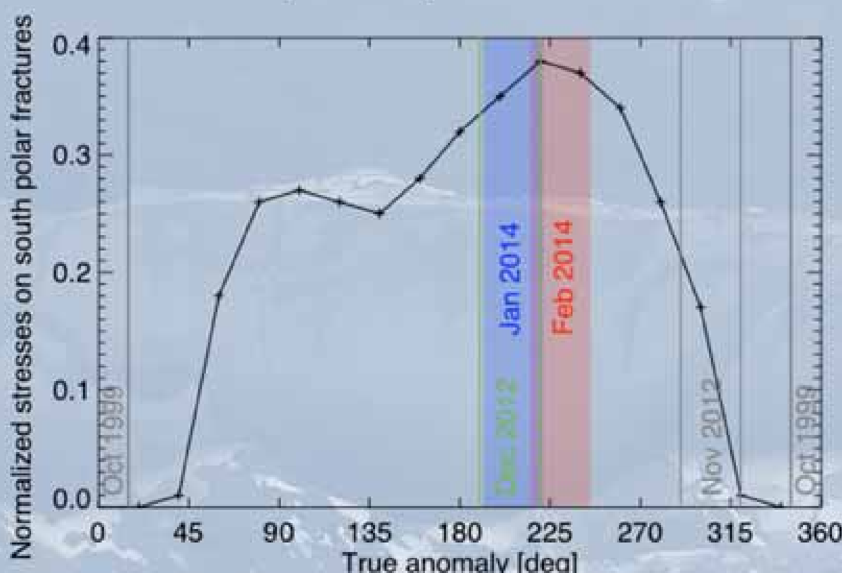
Summary Discussion – Retherford

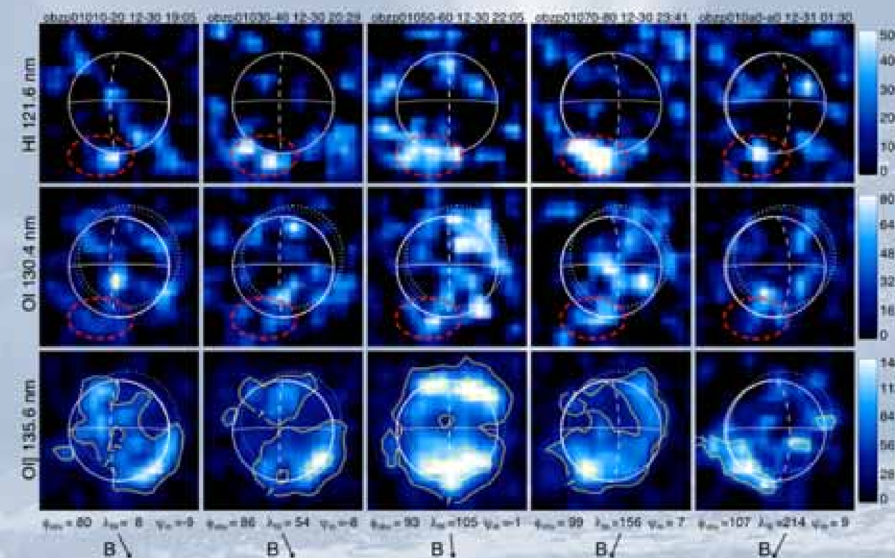
Roth, Sparks, Khurana, Hansen, Kurth, Phillips, Kempf, Schenk, Gudipati

Hubble Datasets:
STIS Far-UV Spectra & Images

- Roth et al. 2014 detections with STIS far-UV spectral images are still best explained by plumes, even if variability not as simple as first thought
- Sparks et al. transit and other far-UV imaging in 2014 have hints of interesting off-limb features (*images not shown here upon request*)

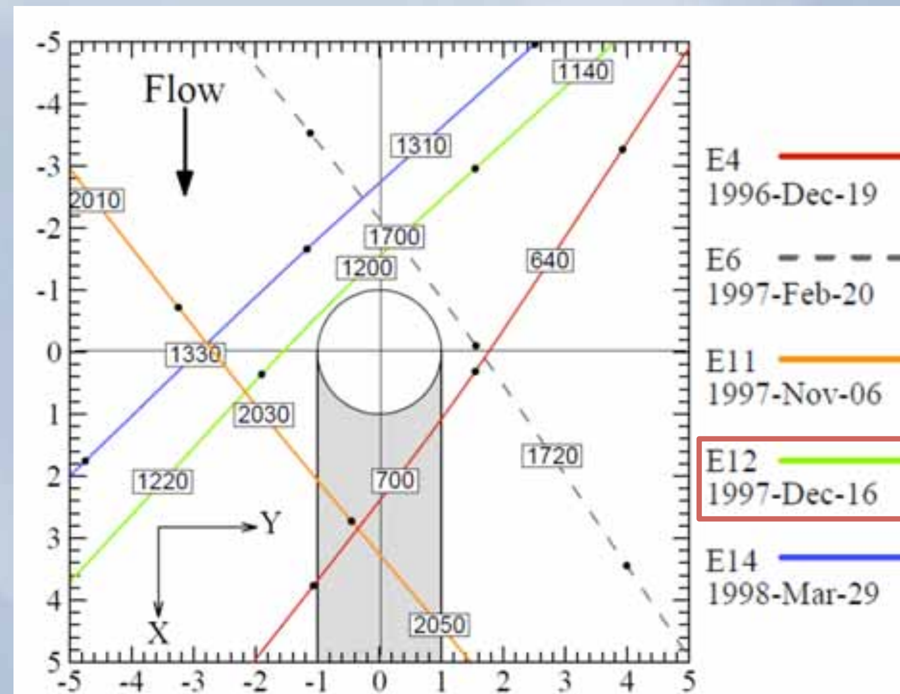


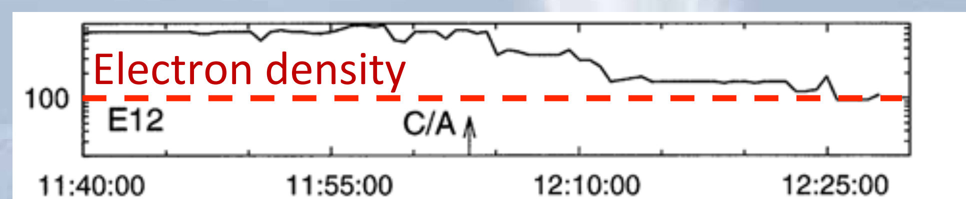


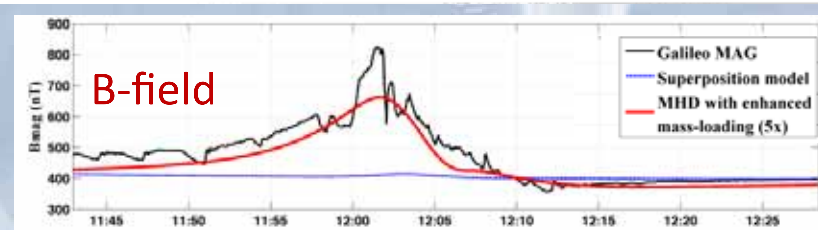


Galileo Fields & Particles E12 Contention

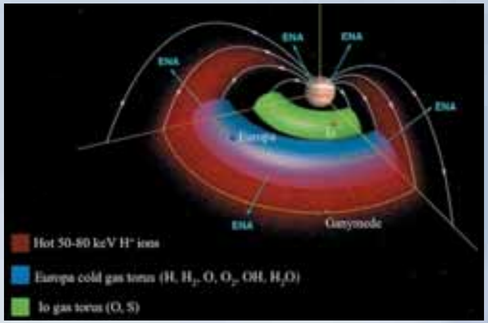
- E12 was an upstream flyby, and seems to show evidence for enhanced neutrals resulting from potential plume activity.
- Electron data from plasma wave instrument, Kurth et al. 2001:
  - Much higher (~ x5) plasma densities in its environment (cf Eviatar & Paranicus 2005)
- Much higher rates of high energy (120-280 keV range) ion loss/cooling in Europa's vicinity.
- Khurana et al. magnetic field data:
  - Much stronger plasma interaction, with a slow down shown in B-field
  - Many tens of kg/s plasma pick-up rate is comparably 5x higher than normal.
  - A plume source for neutral gas is a reasonable explanation
- Group consensus: What are the time scales for delivering neutral gases to upstream region of influence in E12?



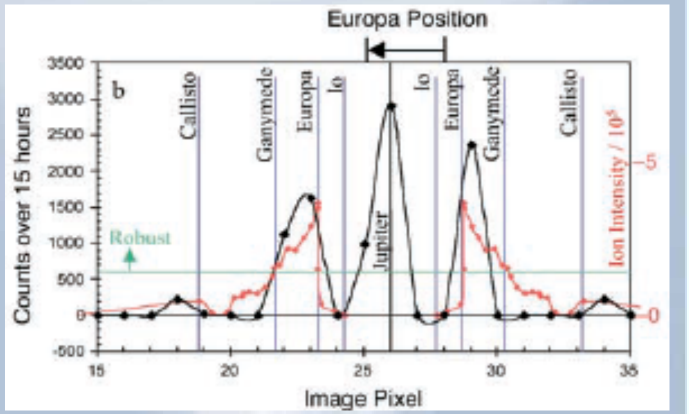




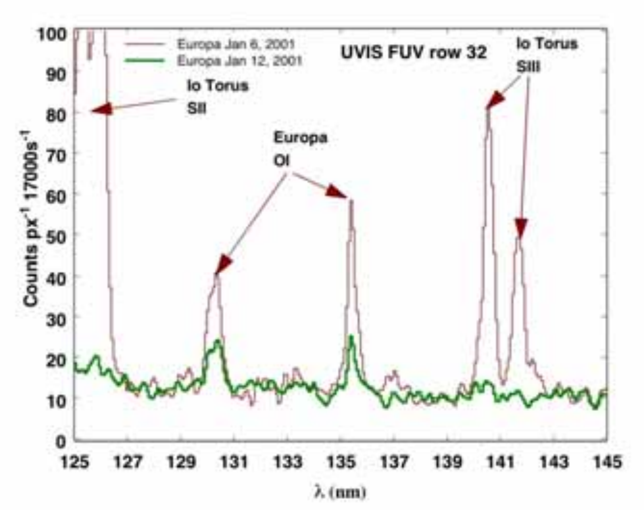
Cassini UVIS & INCA Europa Neutral Torus Connections



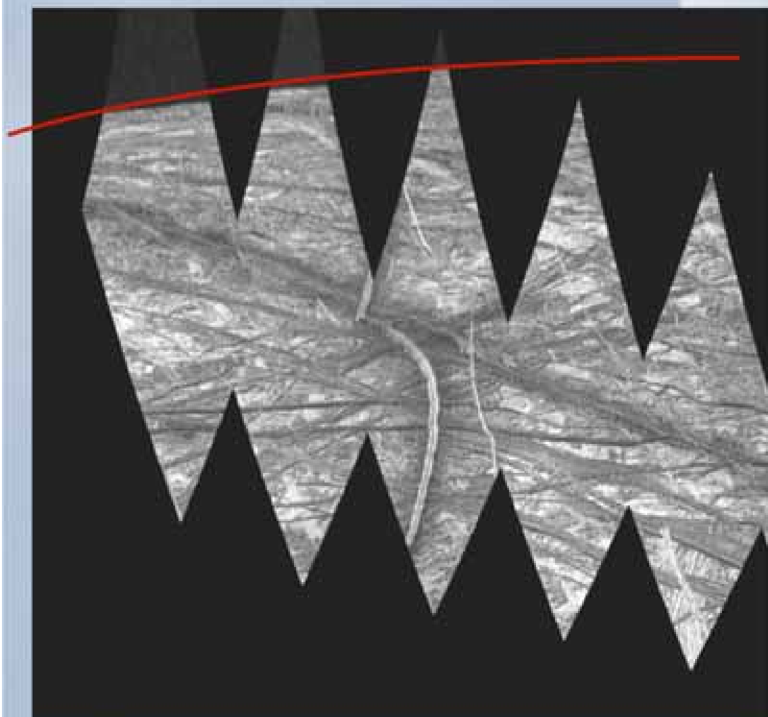
- INCA Energetic Neutral Atom (ENA) data indicate a neutral torus at Europa on par with Io neutral cloud densities (Mauk et al. 2003)
- Mauk et al. 2004 discuss composition of neutrals as mainly H, consistent with but 3x higher than expected from water sputtering calculations by Schreier et al. 1993



- Shematovich et al. 2005 and Smyth & Marconi 2006 both model the sputtered atmosphere in light of Hubble O_2 (Hall et al.) detections and also Cassini UVIS extended oxygen cloud limits (Hansen et al. 2005)
  - Agree that H is supplied more rapidly than O
- New analysis of Cassini UVIS EUV plasma torus species emissions:
  - Sharply rising temperature of outward diffusing plasma from Io with increasing charge state of existing O & S ion particles indicates mass loading is drastically reduced from the level at $5.9R_J$.
  - Implications for Europa-related supply of neutrals: no unusually large injection of neutrals from a plume



Europa Visible Imaging



Galileo E19 Plume search mosaic (Phillips et al. 2000)

- No plumes or anomalous surface deposits are visible in high-phase (~150 deg) limb imaging, but dedicated searches for plumes were limited
- Surface imaging coverage needed to identify icy plumes is inconclusive: need for Europa Clipper

Limited sets of high-phase data for ring observations seem to limit ice-gas ratio to <0.01

- Galileo data were near pericenter (f=10-40°)
  - http://pdsrings.seti.org/galileo/ssi_c10_data.html
- Cassini data exist for >120° phase (Porco et al. 2003 supp.), but apparently wouldn't have detected Enceladus style plumes (Habitability workshop comment)

f ~ 92° (New Horizons LORRI & MVIC)

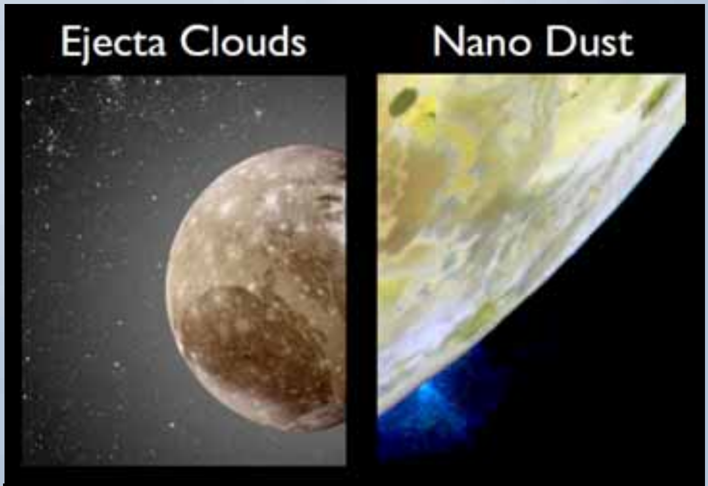
Europa Surface Color & Albedo
Any signs of plume deposits?

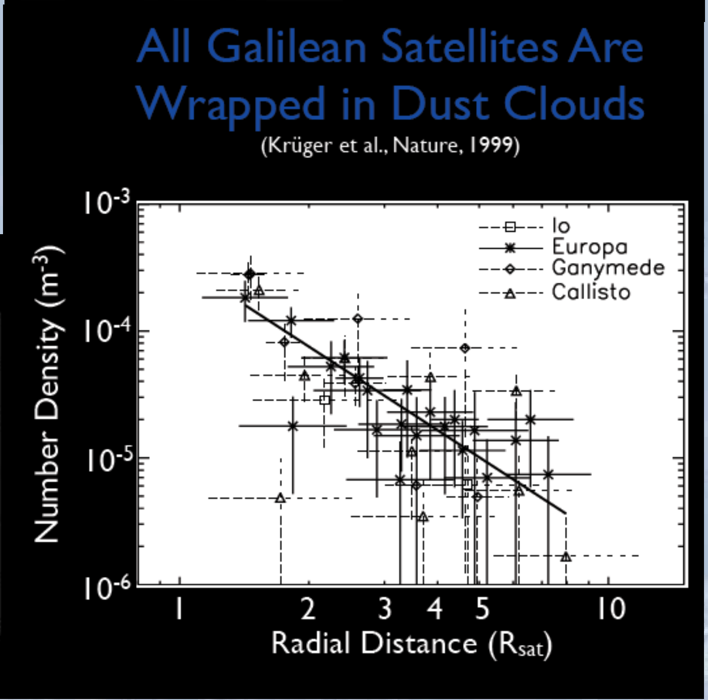
Global IR-B-V color map
(Schenk, Atlas of the Galilean Satellites, 2011)

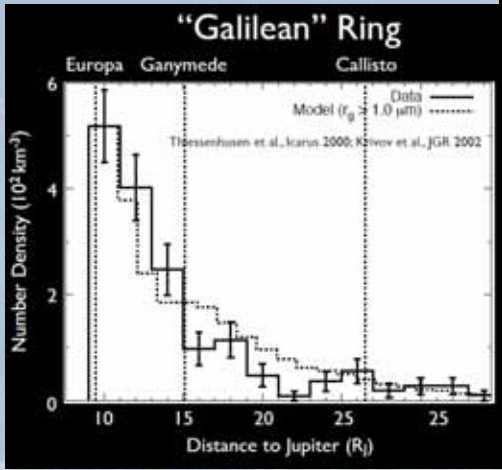
- Enceladus:
  - Plume deposits have stronger UV albedo signature
  - High UV albedo areas match with modeled regions of plume deposits
  - South pole terrain anomalously dark at low phase angles (0-40°)
- Europa:
  - No known anomalies that would indicate plume deposits, only violet enhancement on south leading hemisphere
  - Searches for plumes on Europa must also include surface manifestations, especially if plumes are intermittent or extinct during future missions
  - UV filter set like on Cassini ISS, not provided with Galileo SSI , is needed to search for color signatures

Dust in the Jupiter System

- Dust clouds surround each of the Galilean satellites, resulting mainly from impact bombardments (e.g., LADEE/LDEX measured at Moon)
- Composition of dust distributed outward from Europa's orbit could be ice particles, although improved measurements within 9 R_J are needed
- Numerous useful analogies and lessons from Enceladus plume dust measurements could be applied to Europa (Kempf et al., Postberg, et al.)

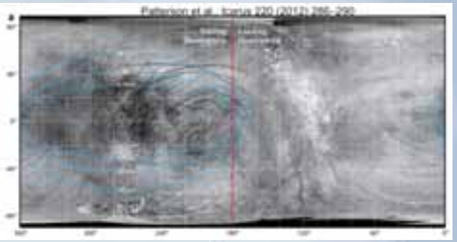






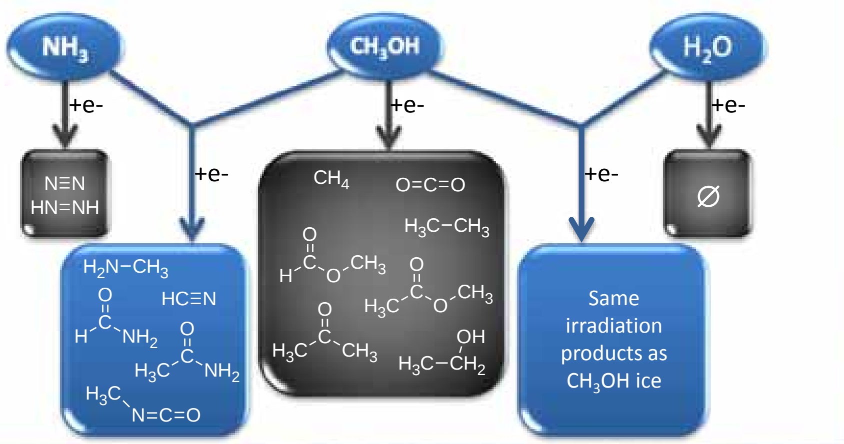
Plumes under Radiation: Ice particles & gas molecules

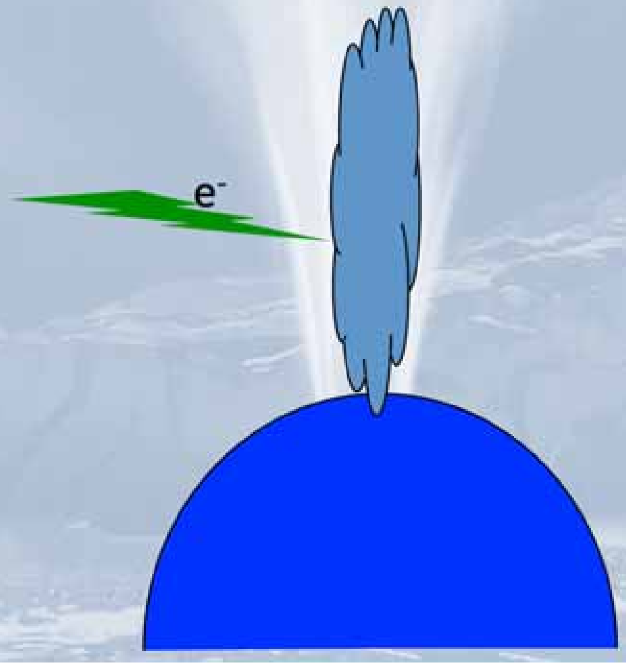
- Murty Gudipati & Bryana Henderson summary
  - Plumes under Radiation would show more complex chemistry than what originally could have been.
  - Ice particles are the source of this complex chemistry
  - Gas-phase molecules undergo dissociation (e.g., methanol to formaldehyde)
  - Quantification is necessary



Radiation (electrons)
Ice → Complex chemistry
Gas → Dissociation
Ionization

Irradiation Products of Single and Dual-Component Ices, 5 K



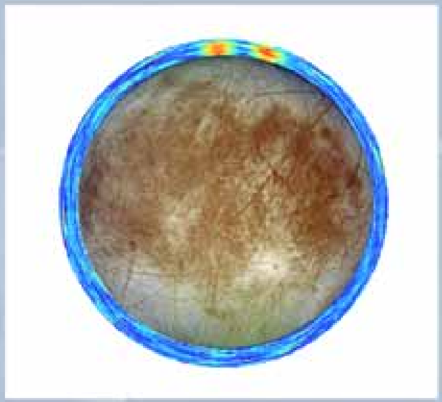


Summary Findings

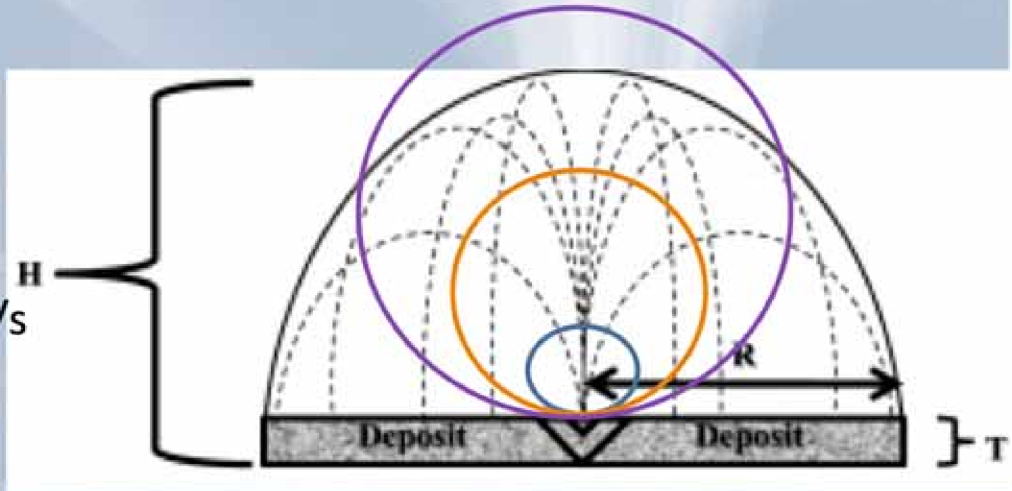
- What do we know?
- What do we need to know?
  - Modeling work
  - Lab work
  - New observations (e.g., Earth-based)
- What measurements should Europa Clipper make?

New Observations Needed

- Earth-based observations, while difficult to resolve plumes from such a distance, will continue to guide mission decisions all the way through JOI
- Hubble observations proposed for next cycle would start ±4 months from Jupiter opposition in early Feb. 2015, influencing Phase A (Step-2) decisions



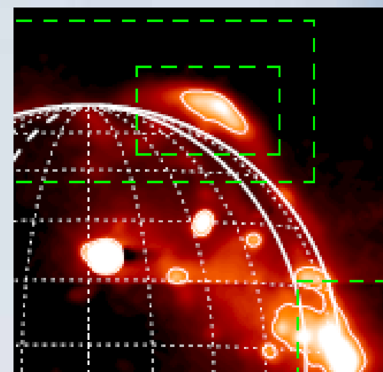
200 km
v=700m/s



R=200km V_{ave}~190 m/s

New Models Needed

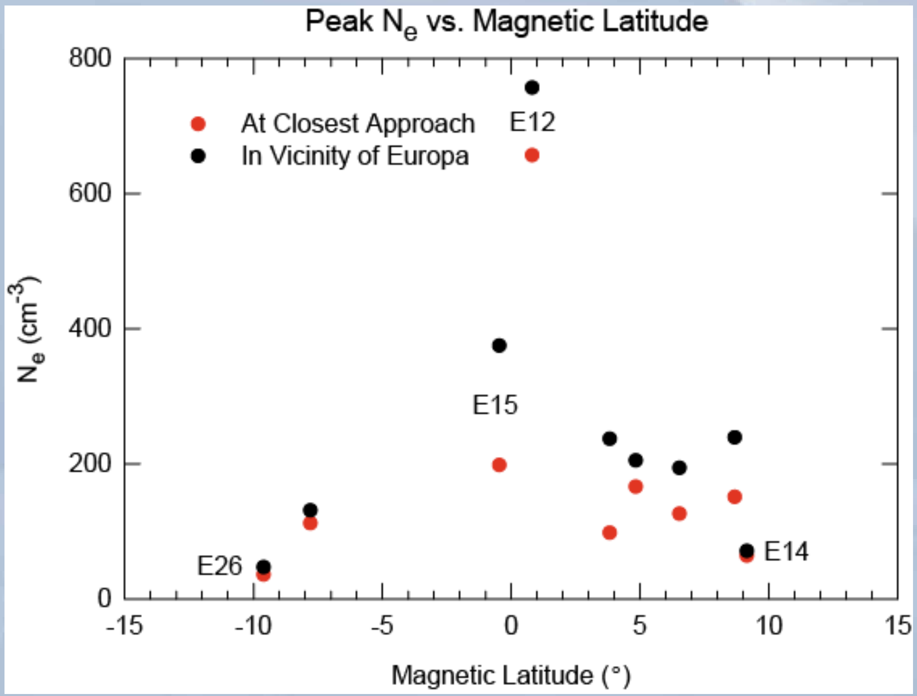
- Plume models – recent RFP will get these going
  - Europa plumes could be an intermediate case between Enceladus and Io
- Europa torus, neutral clouds, and plasma-interaction models would greatly help interpretations of current datasets

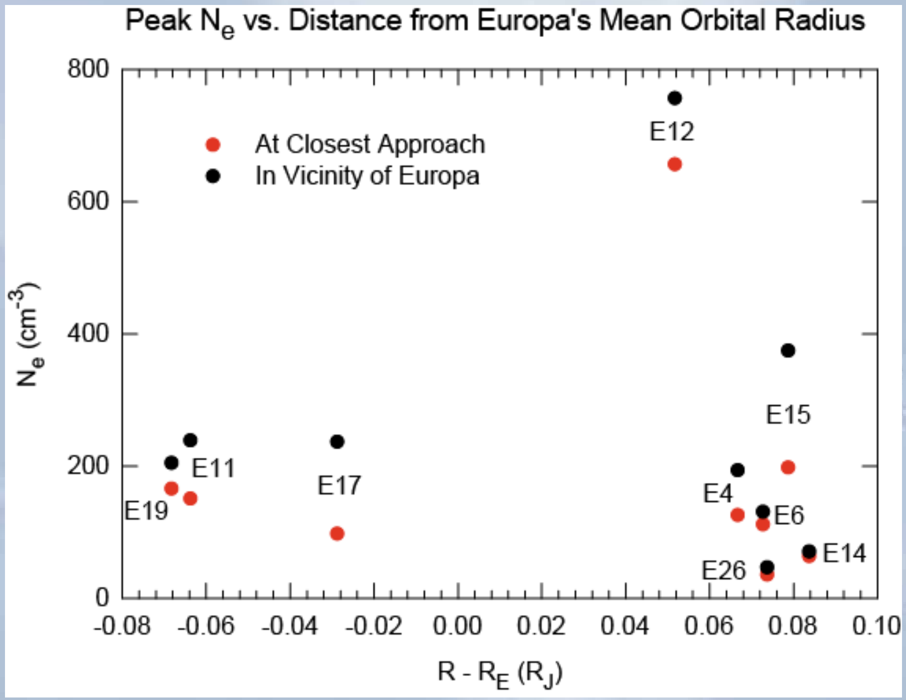


Roth et al. 2011 Modeling of Tvashtar plume aurora

Backup Slide: Galileo E12 Flyby

- Peak bulk plasma densities consistent with Europa's location in/near plasma-sheet (left), but also near apoapsis (right)





Lessons learned at Enceladus

Amanda Hendrix
Presented by Larry Esposito
3 June 2014

What can we learn about Europa - about what is happening geophysically - from what we know about Enceladus?

And what can we learn about what observational techniques to use at Europa from the Cassini experience?

Summary of salient points

- Thermal imaging, UV imaging and monitoring, in situ INMS measurements have been critical techniques for studying Enceladus with Cassini
  - These techniques work whether plumes are dust+gas or stealth (gas-only) plumes
  - INMS results have been dependent on flyby velocity
- Dust measurements have provided critical compositional information that relate plume grains to interior
- Visible, NIR imaging at high phase allow for grain size distribution measurements and also orbital variability studies

- Perhaps it is more appropriate to compare Europa with Io in terms of activity, rather than Enceladus?
  - Sporadic activity on both?
  - Europa may be a young Io?

Structure and Composition

- Remote sensing can monitor Europa activity through systematic scans of the Jupiter system
- Closer to Europa: thermal infrared, near IR, UV occultations and multicolor images can identify active sites and measure plume morphology
- Mass spectroscopy provides the most sensitive composition measurements

Dust in the plume

- Provides information on the interior
- Is best detectable at high phase or in-situ
- Is a potential spacecraft hazard
- Shows periodic activity and possible secular changes at Enceladus

Enceladus plume and geophysical models

- Extend and explain spacecraft observations
- Test plausible hypotheses
- Provide information on history and evolution

Flexible & Comprehensive Cassini Enceladus Observations

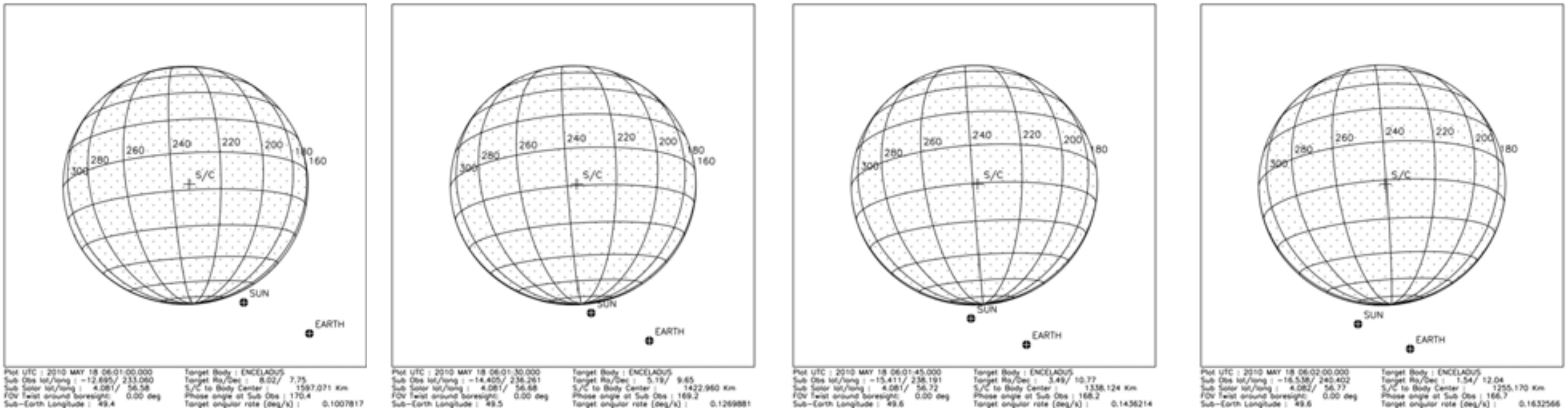
- Combine monitoring, remote sensing and in-situ measurements
- Provide multiple approaches to determine habitability
- Provide a good estimate of plume risk
- Identify possible future exploration locations

Enceladus Plume: Structure, Composition, Variability, Hazards

Larry W. Esposito

2 June 2014

Solar Occultation Geometry



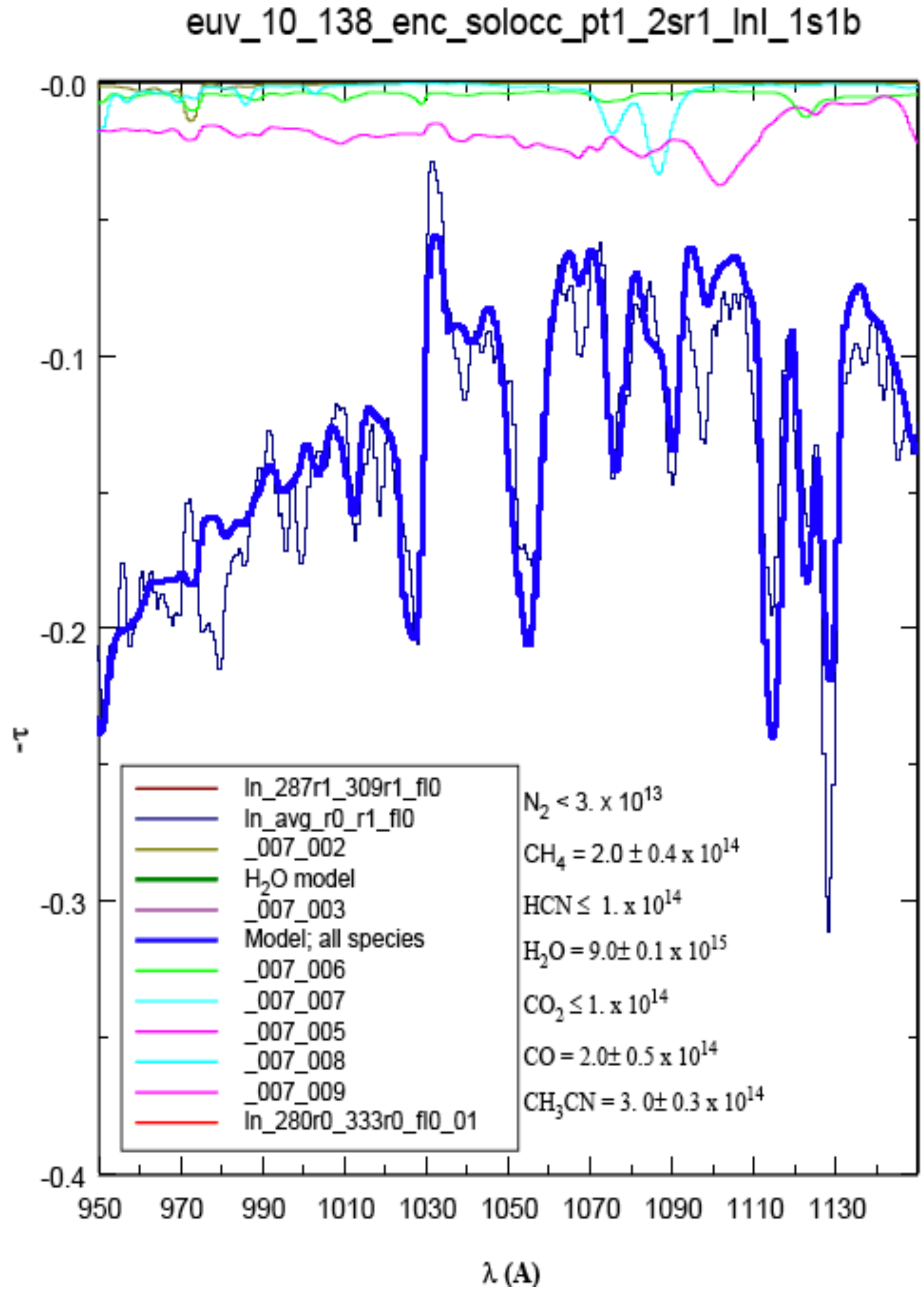
The sun was occulted by Enceladus' plume 18 May 2010

Two science objectives enabled by solar (rather than stellar) occultation:

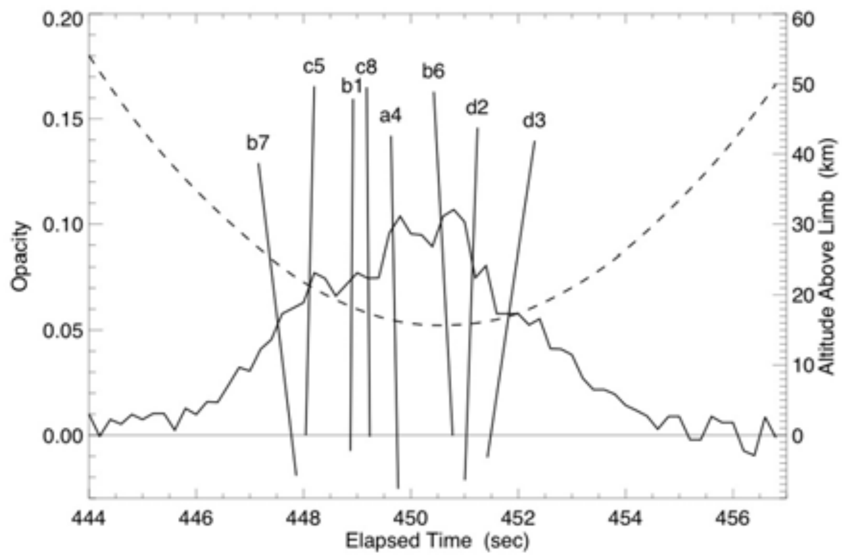
1. Composition of the plume
   New wavelength range
2. Structure of the jets and plume
   Higher spatial resolution

Enceladus
Plume Composition

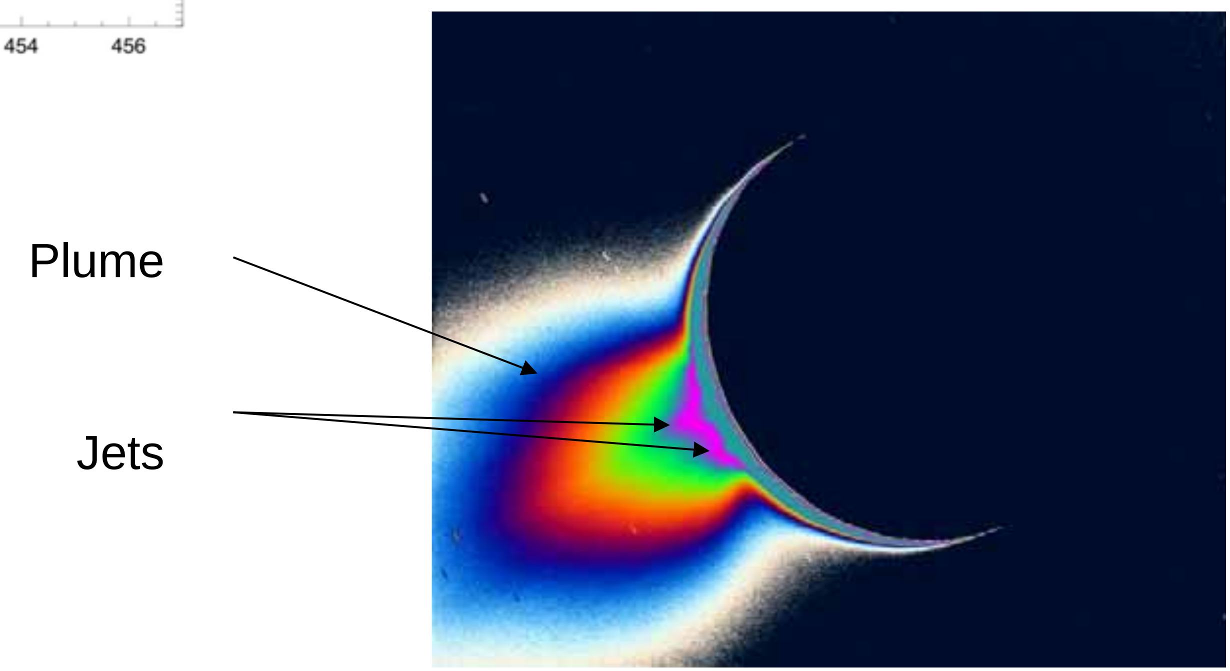
- UVIS solar occ finds water amount same as from star occ’s
- Nitrogen upper limit: 0.3%



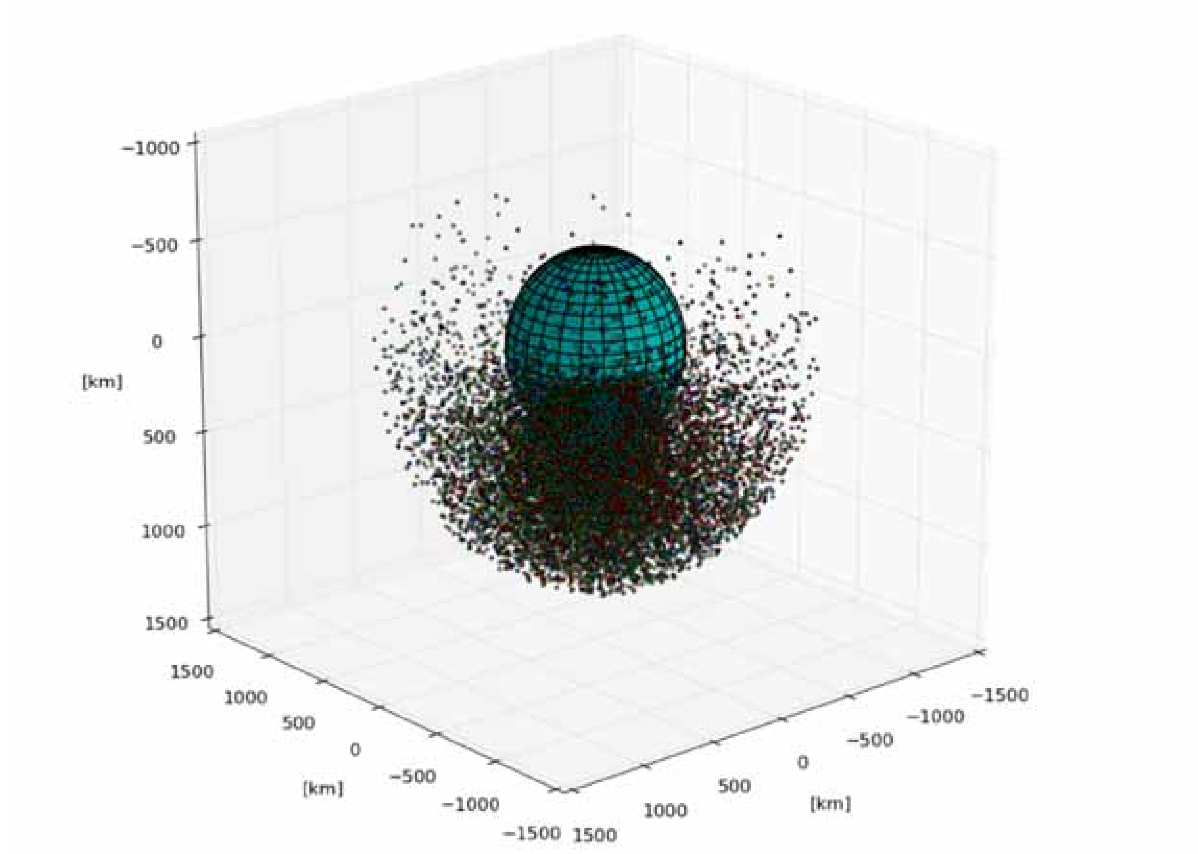
Plume Structure and Jets



Density in jets ~2x density in background plume



3D distribution of water molecules from Enceladus



Number of dangerous particles

- Calculate the predicted number of hits by dangerous particles (r > 900 microns) if spacecraft flew a path with same altitude as at Enceladus:
- $N_D = f_1 * (4-q)/(q-1) *$

  $a_0^3/(a_{max}^{4-q} - a_{min}^{4-q}) *$

$(a_*^{1-q} - a_{max}^{1-q})$

OH in the Saturn system

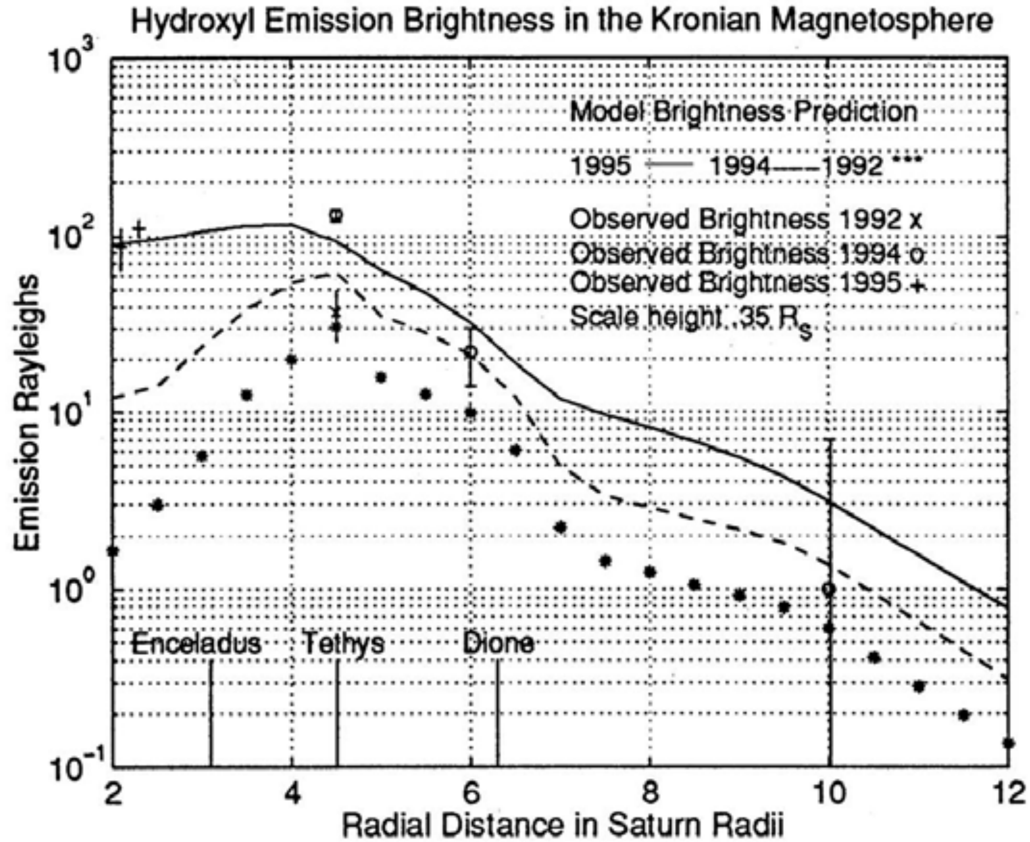


Figure 5. Brightnesses of OH inferred from HST observations (points) with 1σ errors. Model OH emission profiles for the 3 epochs are shown by the lines.

Shemansky et al., 1993; Richardson et al. 2005

Oxygen in the Saturn system

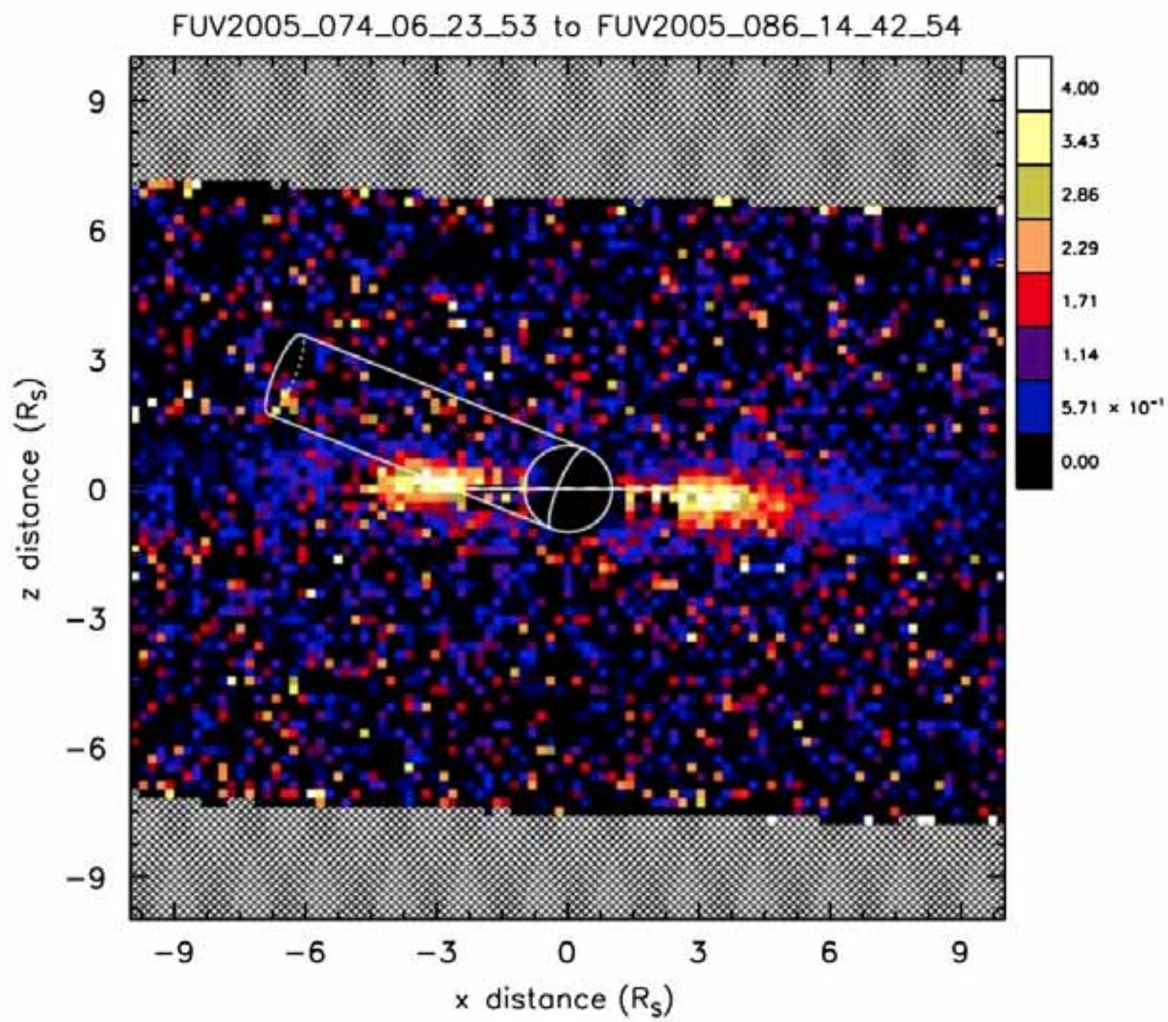
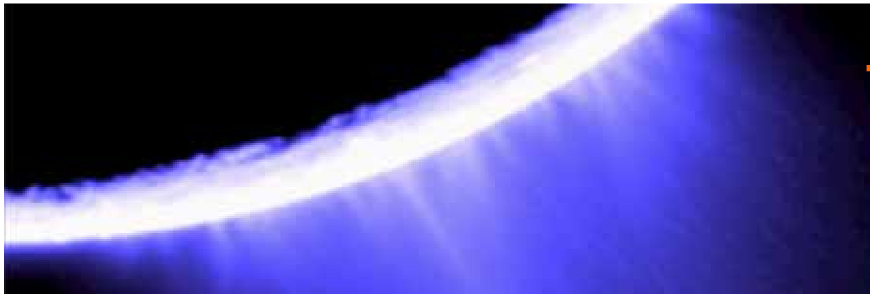


Fig. 18. OI 1304 Å map of Group 7 (2005-074), as defined in Tables 1 and 2, rendered at a resolution of $0.1 \times 0.1 R_S$. Note that the intensity scale has a maximum value of 4 Rayleighs per mosaic element.

Melin et al.



The Enceladus Ice Plume

Frank Postberg, Univ. Heidelberg & Stuttgart

- Total ice particle emission:
  10 – 50 kg/s (CDA), up to 100 kg/s (ISS) → 5 – 50% of gas flow (≈200 kg/s)
- Size distribution in plume:
  power law with slope of about 4 (VIMS, CDA, ISS)
- Most particles r < 1µm / some 1 - 5µm / none r > 10µm
- Ejection speed moderated by wall collisions in the vents:

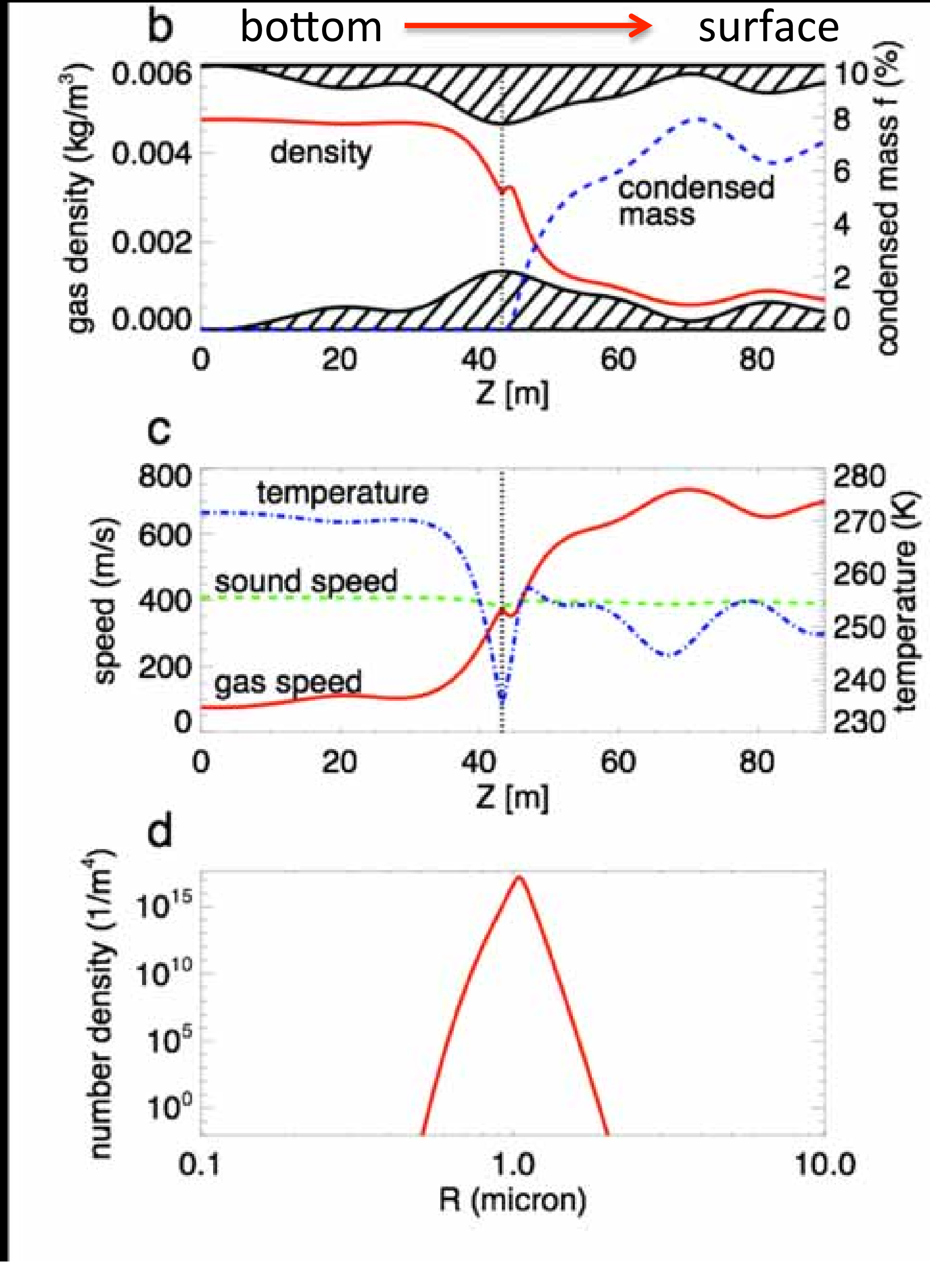
  Ice: V_e < 400 m/s (escape speed ≈250 m/s)

  Gas: V_e = 400 – 1500 m/s
- Generation of ice grains:
  - (comet-like fragmentation of solid ice)
  - homogenous nucleation in the vent
  - heterogeneous nucleation

Homogeneous Nucleation in the Vents

Schmidt et al. (2008)

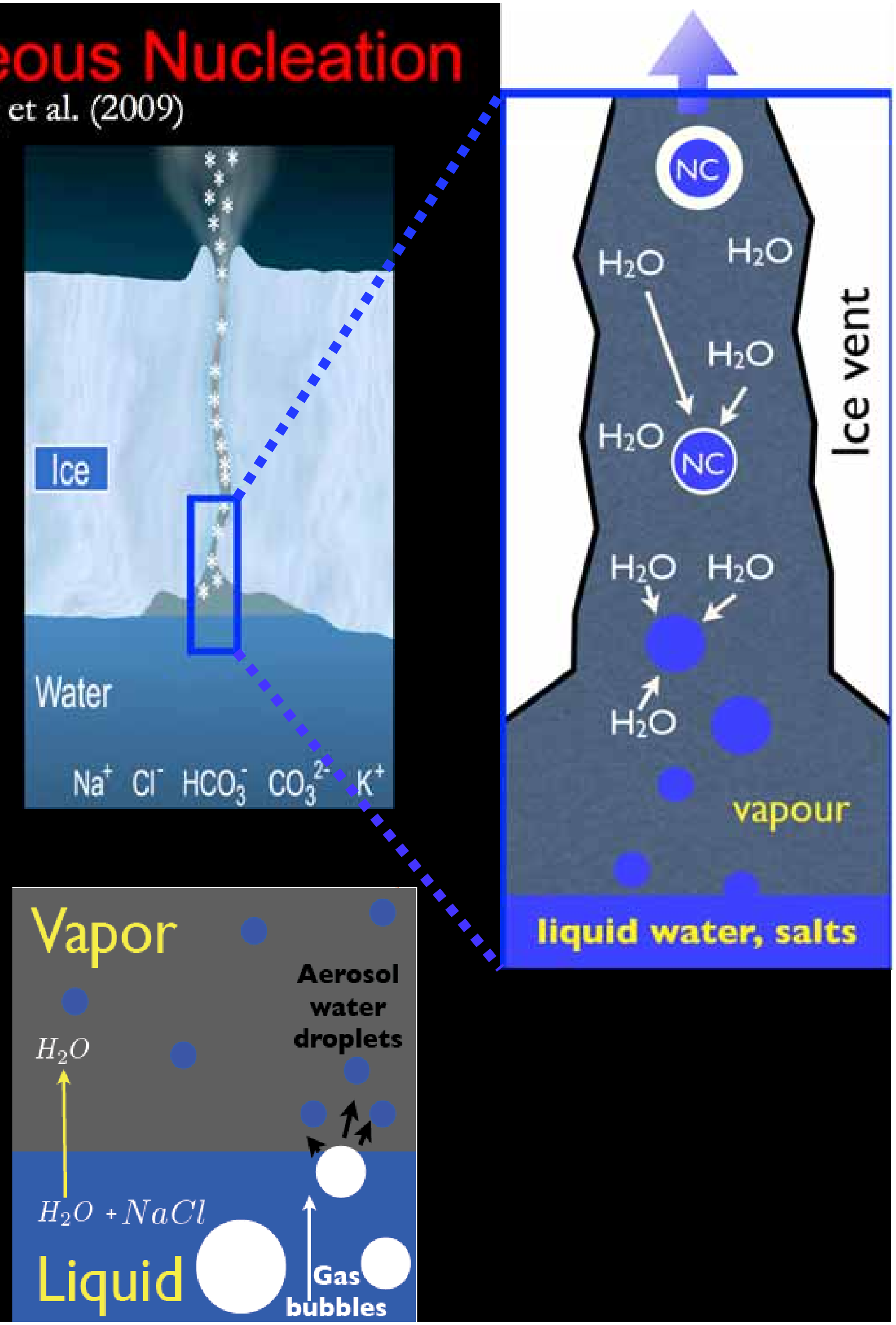
- Spontaneous vapour nucleation when gas flow becomes supersonic
- Inherits refractory part of vapour composition
- Very well reproduces abundance and sizes of particle population up to about r =1.5 μm
- Underestimates abundance of particles r $\geq$ 2μm (Hedman et al., 2009)
- Ejected with rel. fast speed
- Particles dominant in fast jets & high altitudes & E ring



Heterogeneous Nucleation

Postberg et al. (2009)

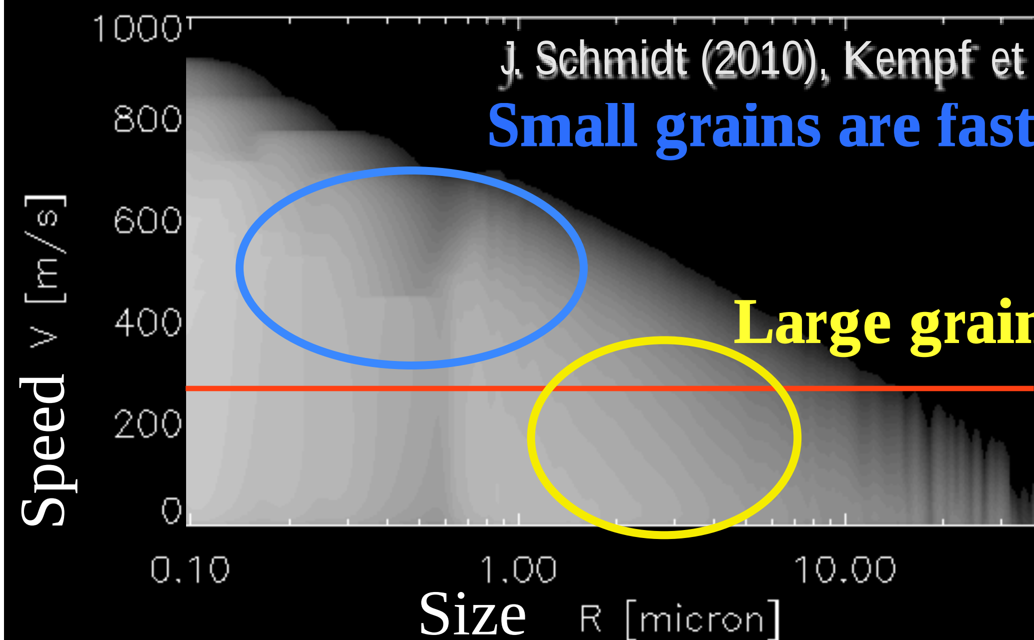
- Ice grains grow from nucleation core
- Aerosol-like spray above liquid (sub-μm - few μm)
- Inherits composition of subsurface water
- Starts with rel. large nucleation cores → produces larger grains than homogenous nucleation
- Mostly ejected at slower speed than smaller vapour nucleated grains
- Particles abundant at low altitudes (< 50km), depleted at high altitudes & E ring

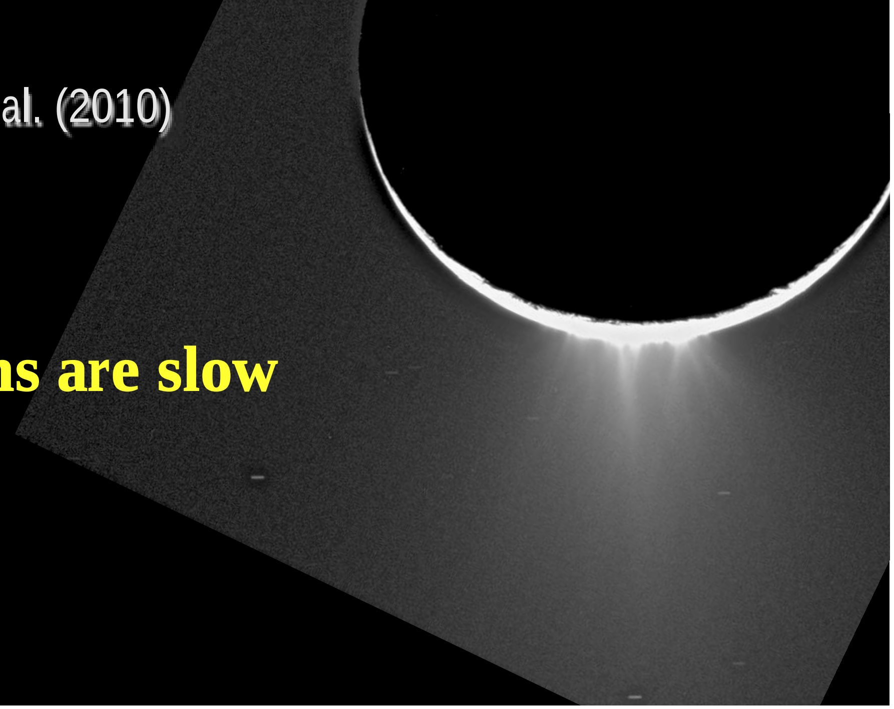


CDA: Compositional Types of Icy Grains

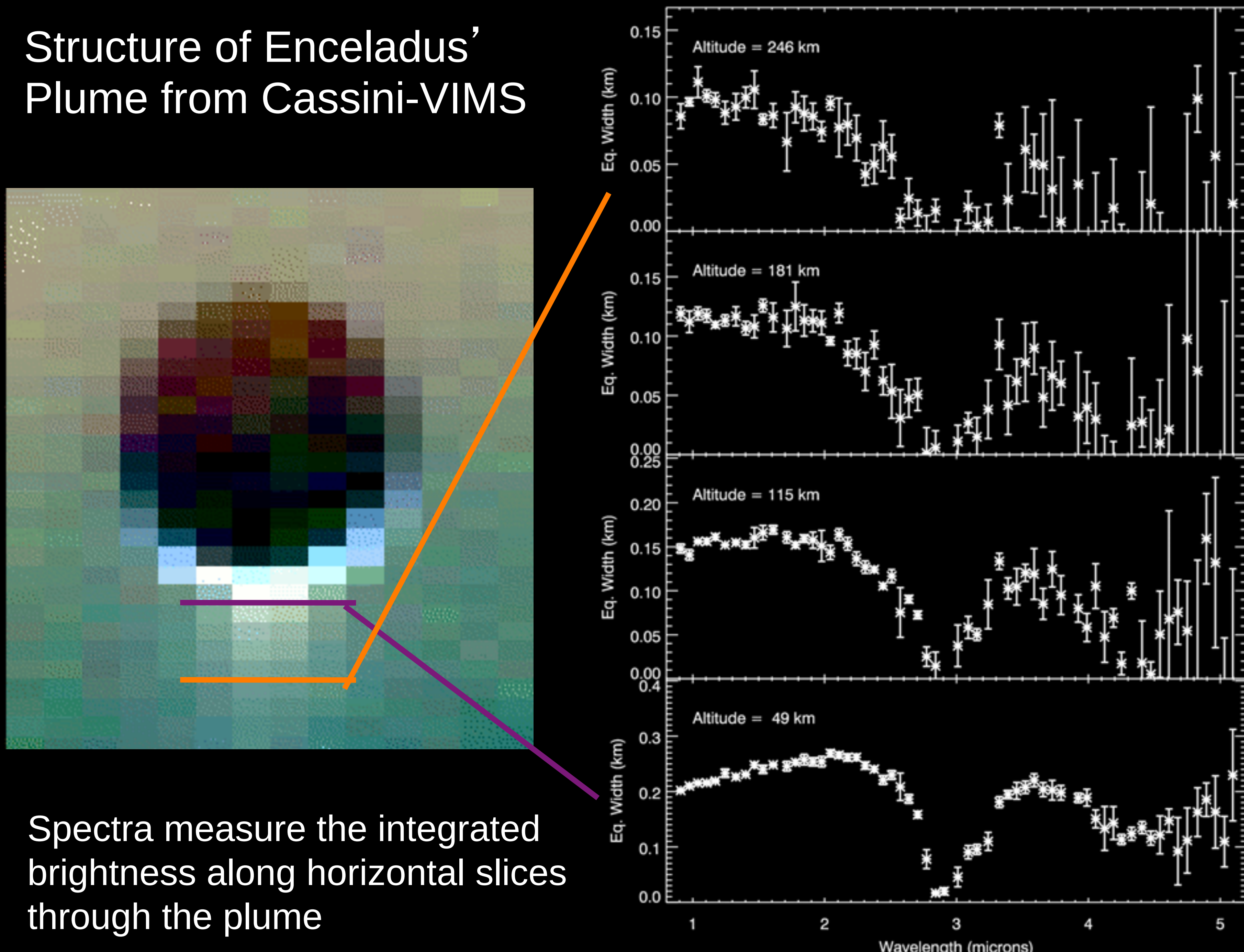
Hillier et al. (2007); Postberg et al. (2008, 2009, 2011)

- Type I — Small / almost pure water ice + salt poor
  → Homogeneous nucleation
- Type II — Larger / Water ice with organics + mostly salt poor
  → Mostly homogeneous nucleation (?)
- Type III — Largest / salty water ice (0.5 - 2% NaCl, $NaHCO_3$/Na_2CO_3, KCl)
  → Heterogeneous nucleation from aerosol spray above liquid water





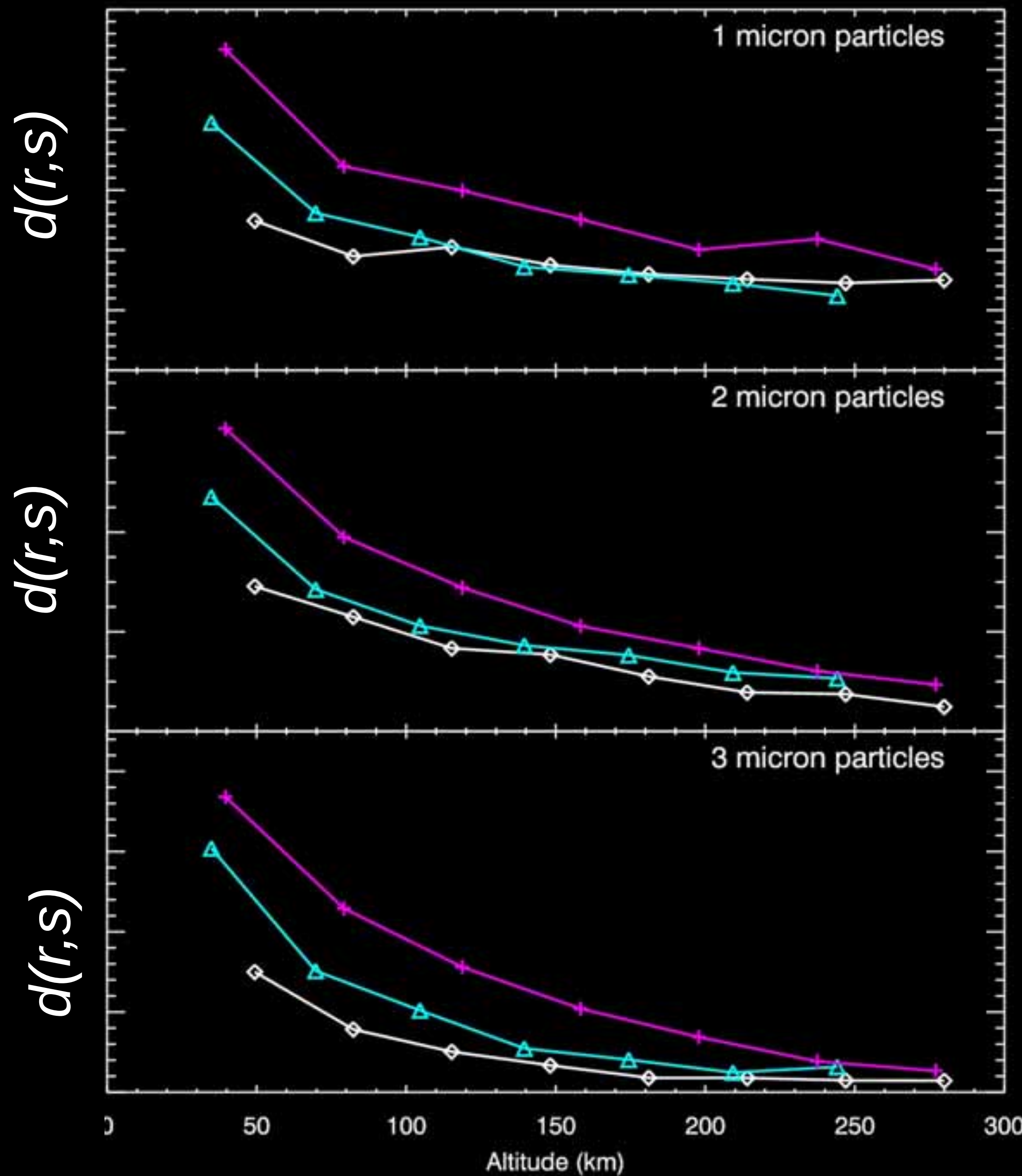
Structure of Enceladus' Plume from Cassini-VIMS



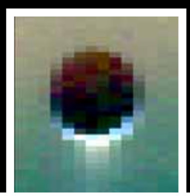
Spectra measure the integrated brightness along horizontal slices through the plume

These spectra can be used to determine the particles' spatial distribution and launch velocity distribution.

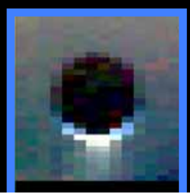
Note the density of larger particles falls off more steeply



Cube 1

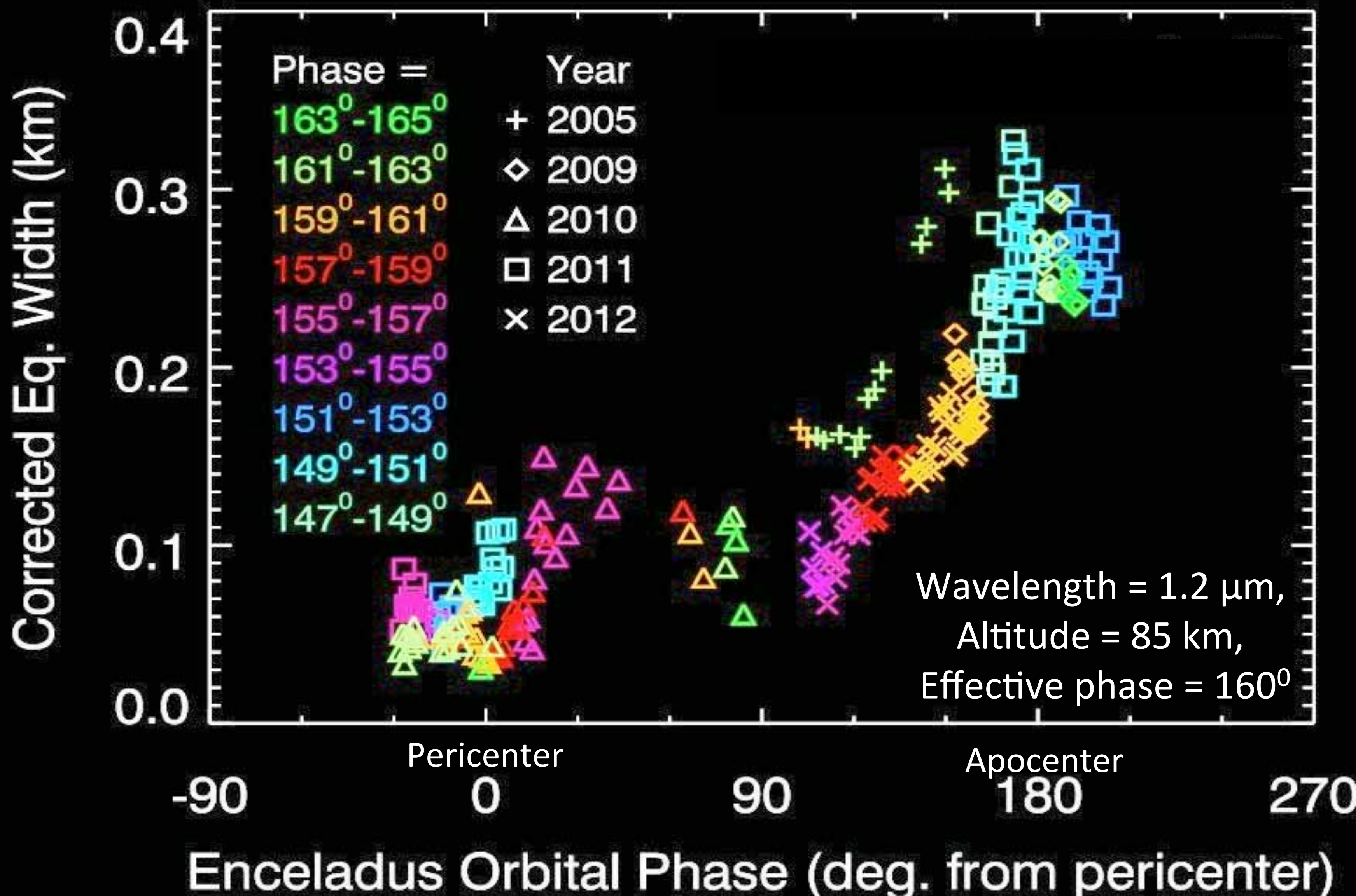


Cube 2

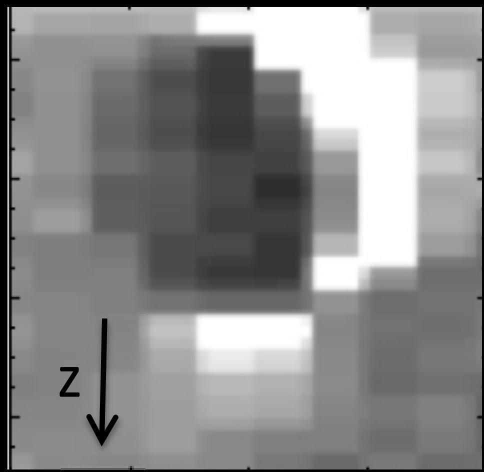


Cube 3

These observations also document variations in the plume's total output with orbital phase

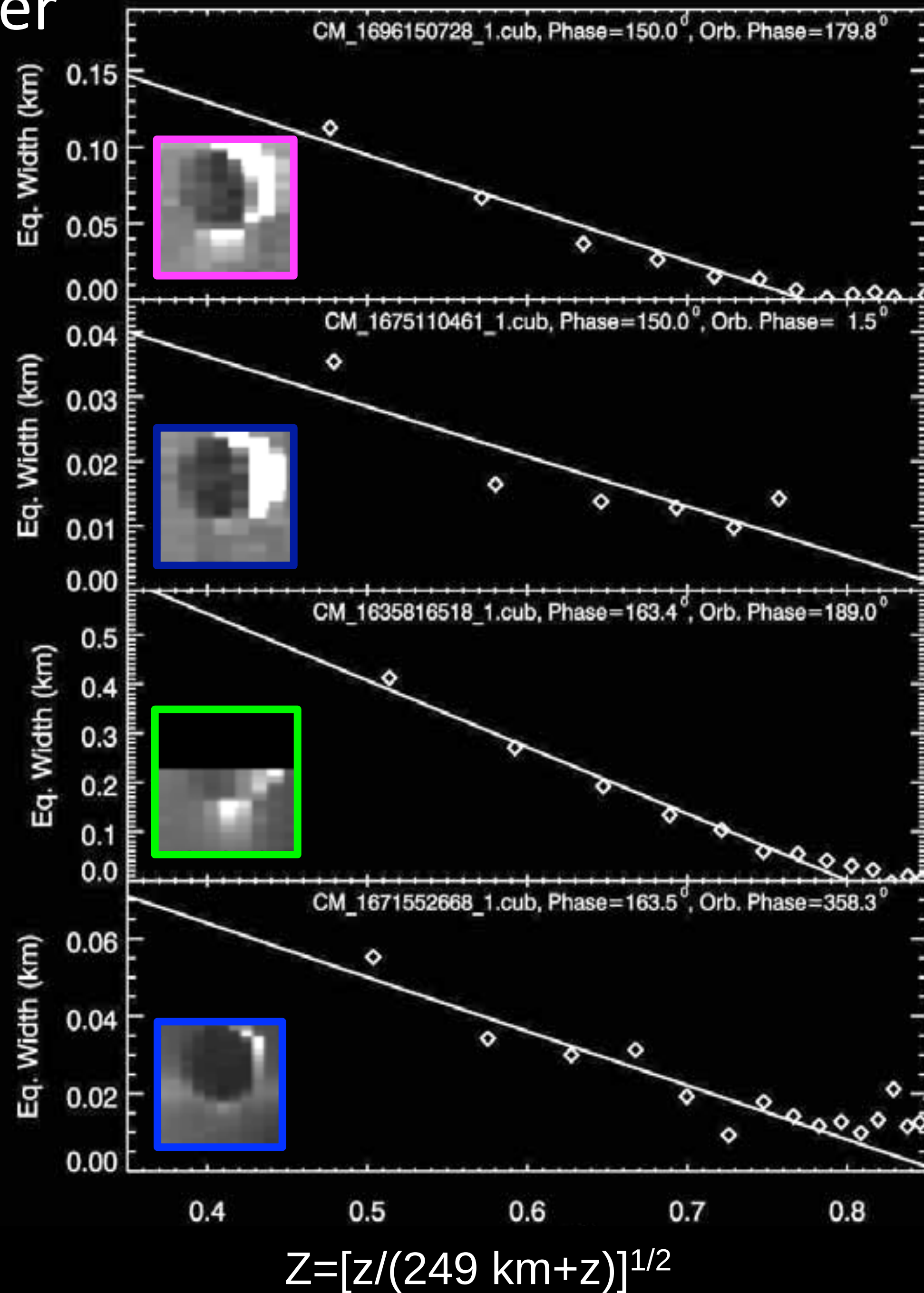


Looking for variations in other observables: Scale Height



These plots show the integrated brightness versus the parameter $Z=[z/(249\ \mathrm{km}+z)]^{1/2}$, which is a proxy for the particle's launch velocity.

Note the x-intercepts for the profiles vary systematically with orbital phase, which indicates a subtle shift in the maximum launch velocity.



The Plume Composition of Enceladus derived from the Cassini-INMS

How can we use composition information to determine past or ongoing processes in the interior?

Enceladus Composition Summary

Volatile Species	H_2O	CO_2	CH_4	NH_3	H_2	CO or N_2	HCN or C2s	CH_3CN	CH_2O
True Plume mixing ratios (E14, E17, E18)	>84%	.3-.8%	.1-.3%	.4-1.3%	0-15%	CO: 0-0.9% N_2: 0-0.9%	HCN: 0-0.2% C_2H_2: 0-0.04% C_2H_4: .12-.14%	less than .006%	less than 0.03%
Ice Grain mixing ratios (ibid)	>74%	0.6%	0.2%	Not seen	0-22%	CO only: 2%	HCN, C_2H_4, C_2H_2: <0.1%	0.01-0.02%	<0.01%
Fast Flyby Mixing ratios (E5)	>60%	2-9%	1-2%	0.1-1%	0-38%	CO: 1-7% N_2: <4%	HCN, C_2H_2: <1% C_2H_4: <2%	less than <0.1%	less than 0.5%

Hydrothermal modification

Shock and McKinnon, Icarus, 106, 464-477, 1993

Mineral Equilibria

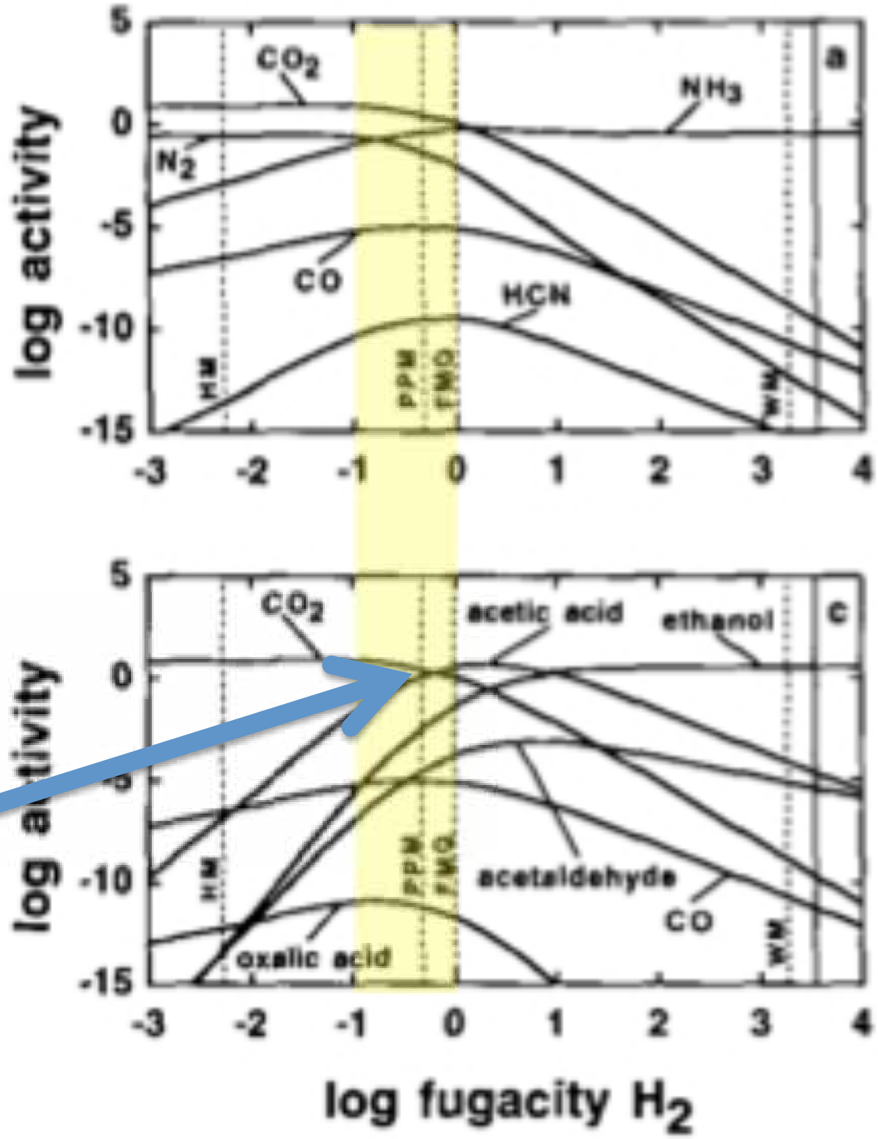
$$\underset{\text{magnetite}}{2\,Fe_3O_4} + H_2O = \underset{\text{hematite}}{3\,Fe_2O_3} + H_2, \qquad \text{HM}$$

$$\underset{\text{pyrrhotite}}{2\,FeS} + 4/3\,H_2O = \underset{\text{magnetite}}{1/3\,Fe_3O_4} + 4/3\,H_2, \qquad \text{PPM}$$

$$\underset{\text{fayalite}}{3/2\,Fe_2SiO_4} + H_2O = \underset{\text{magnetite}}{Fe_3O_4} + \underset{\text{quartz}}{3/2\,SiO_2} + H_2, \qquad \text{FMQ}$$

$$\underset{\text{wüstite}}{3\,FeO} + H_2O = \underset{\text{magnetite}}{Fe_3O_4} + H_2, \qquad \text{WM}$$

Figure 6 temperature 200 degrees C, 3500 bars pressure



1. Equilibrium calculations of log activity of aqueous species versus log of H_2 fugacity.
2. The region of near equal concentrations of NH_3, N_2, and CO_2 as observed is marked in light yellow.

1.The acetic acid may be the source of compounds that are further processed to form the observed hydrocarbons.
2. McCollum et al. (2010) has shown COOH compounds may form hydrocarbons with ratios of C1 to C2 to C3 hydrocarbons similar to those observed.

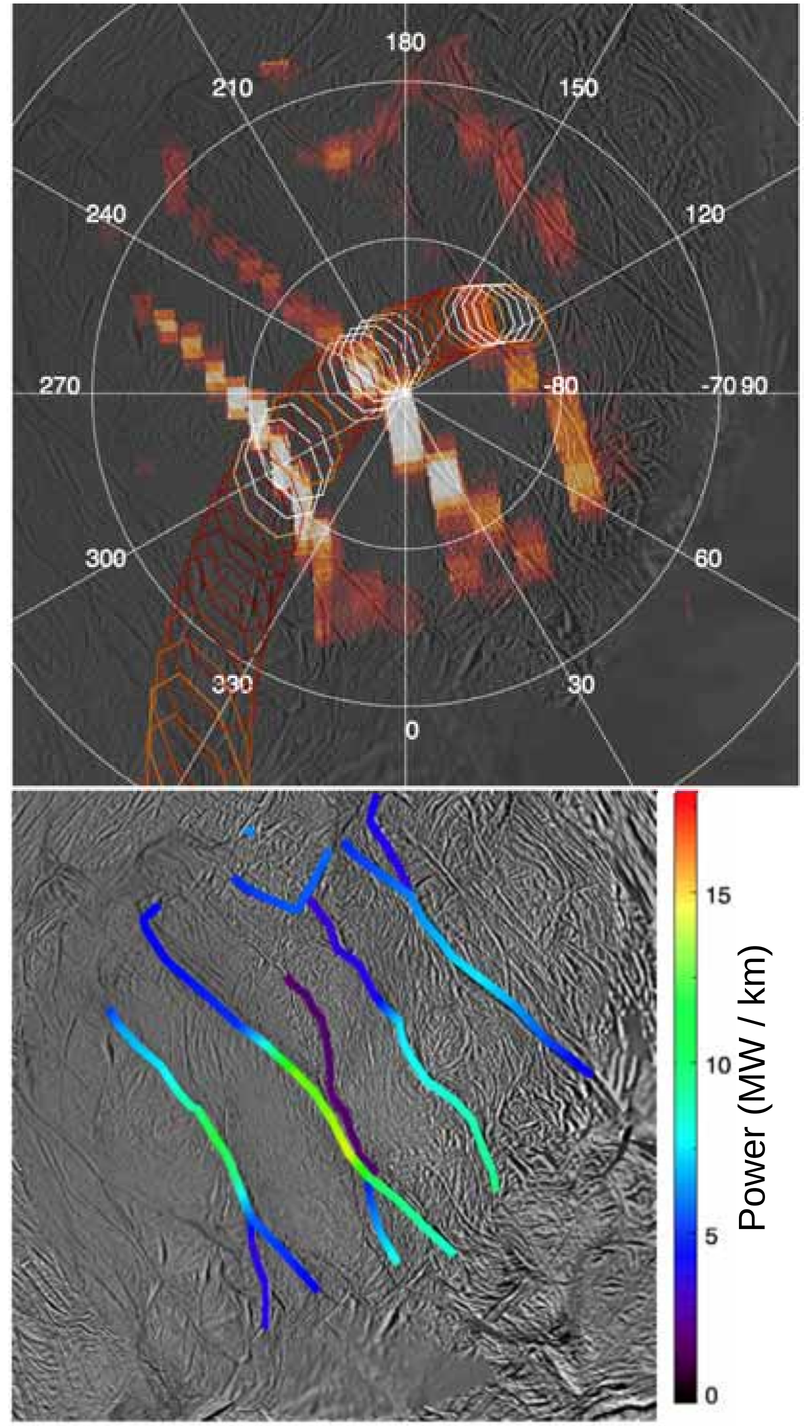
Enceladus Thermal: Kickoff Slides

John Spencer

Europa Plume Workshop
June 2[nd] 2014

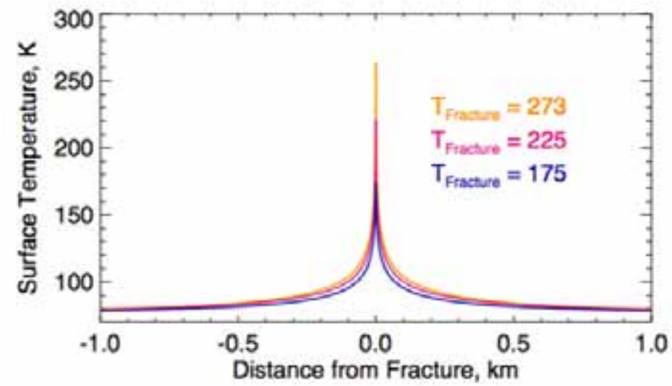
Enceladus Plume Source: Thermal Signature

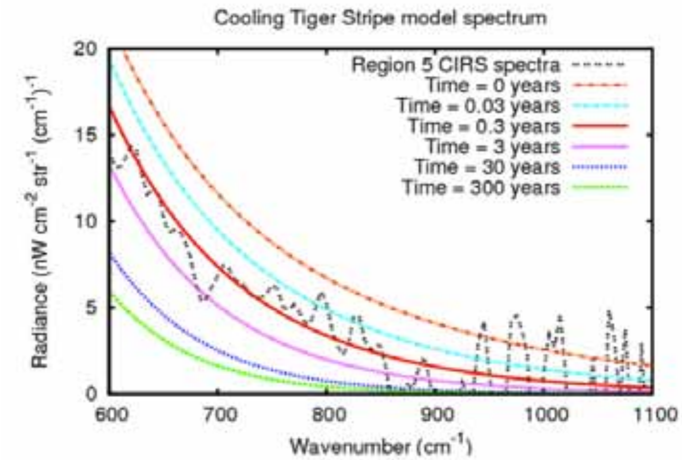
- ~4.5 GW of emission from the tiger stripes at 4 – 200 μm (Spencer et al. 2013)
  - Possibly many more GW radiated at low temperatures between the tiger stripes?
- Peak temperatures ~200 K (Goguen et al. 2013)
- Narrowly confined to fractures
  - Warm regions 100s of meters wide
  - Active fissures ~few meters wide
- Nearly continuous emission along-strike, but large variations on scales down to sub- kilometer
- Nearly 1:1 correlation between thermal emission and plume activity
  - Some evidence for cooler, dormant fractures, however

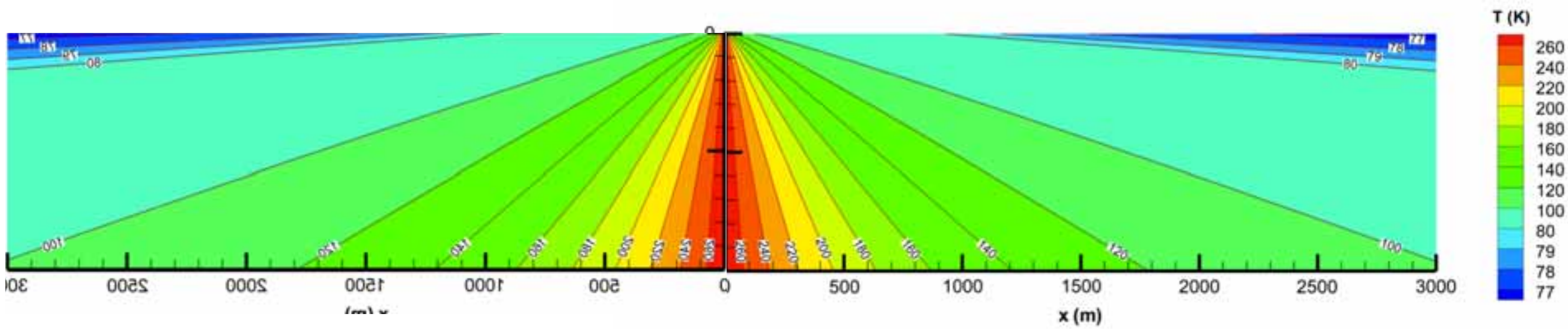


Understanding the Thermal Signature

- Consistent (to first order) with conductive heating of walls of a uniform-temperature fissure (Abramov and Spencer 2009)
  - Fissure temperature ~200 K (Goguen et al. 2013)
- Several active fissures are required in the most active regions to match the emission amplitude
  - Thermal signature will persist for decades (Abramov and Spencer 2008, 2009)
- Typical radiated powers of ~10 MW/km can be matched by condensation of water vapor onto fracture walls (Ingersoll and Pankine 2011)
  - Several fractures required in most active regions
  - Condensation seals fractures on ~1 year timescales

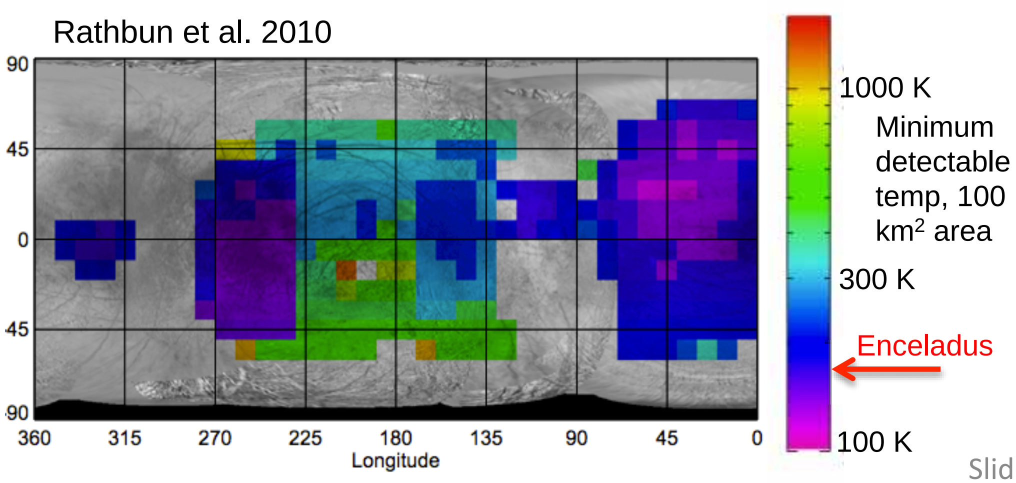


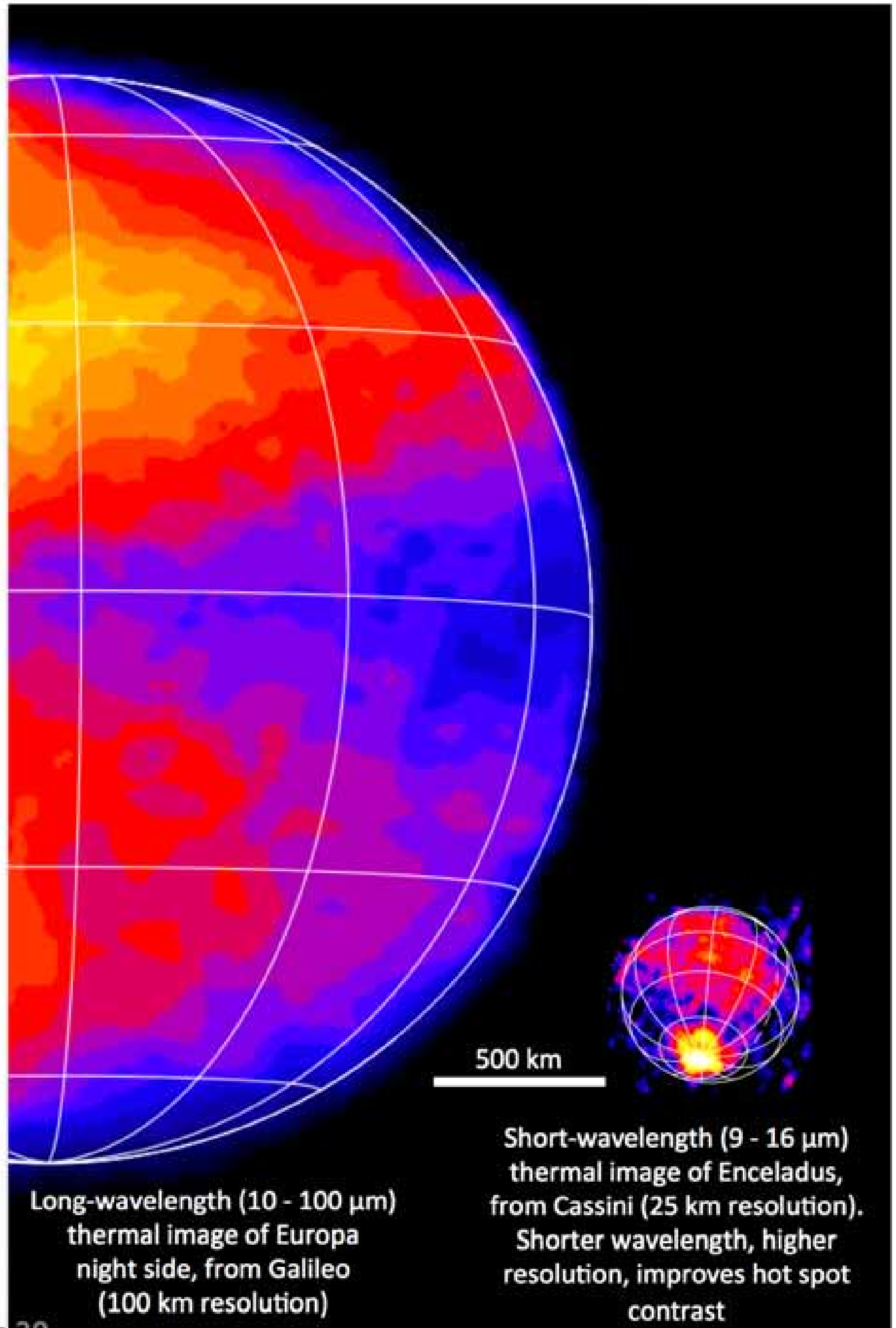




Application to Europa

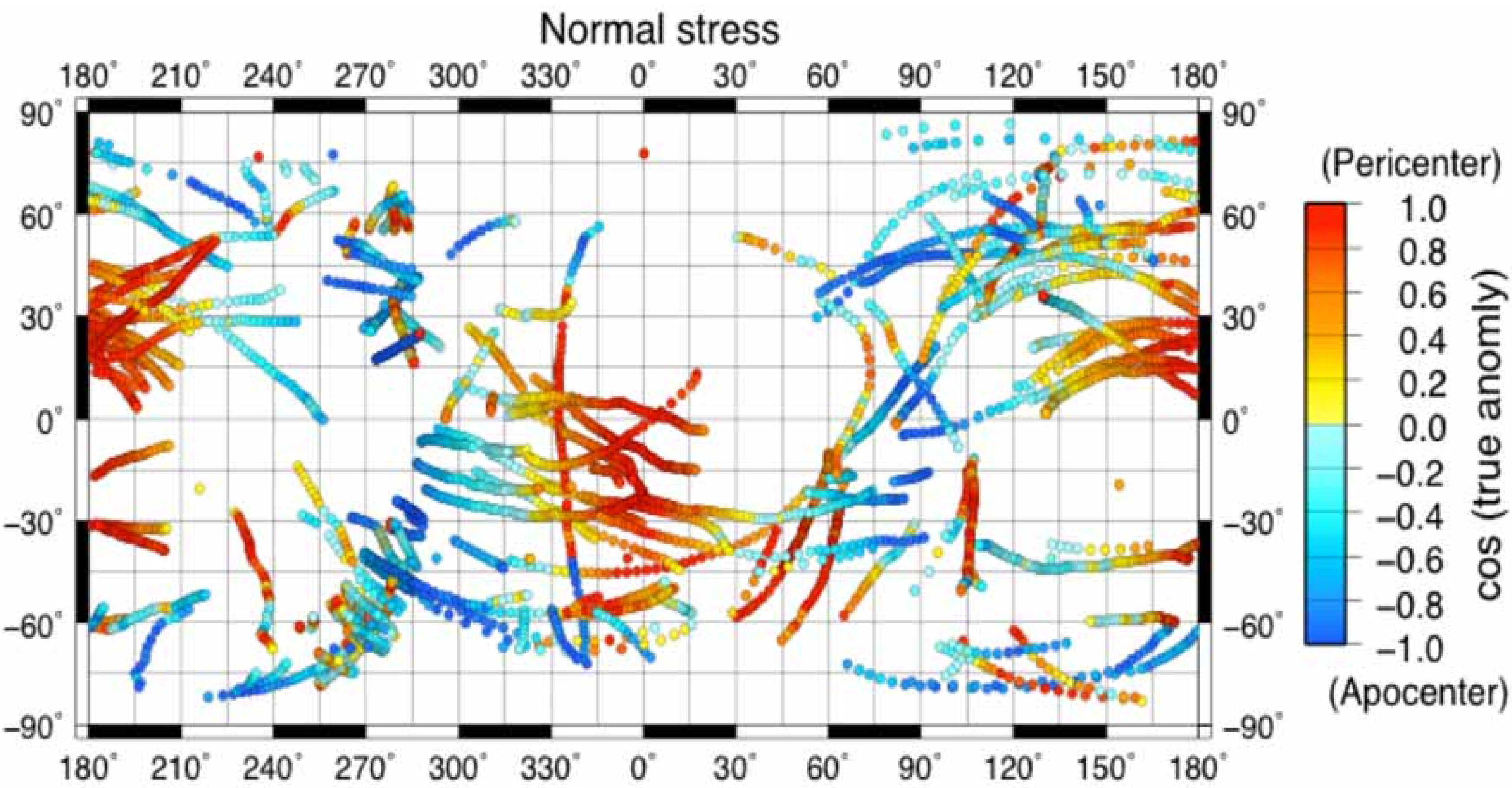
- Thermal mapping pinpoints plume source sites, and other activity sites, without requiring special limb geometries
- Signature likely to persist for years even if plume activity is intermittent
- Provides unique information on plume source conditions
- Thermal mapping of Europa is patchy and low-resolution
    - Enceladus-like thermal anomalies, including in the southern “plume” area, could easily go undetected





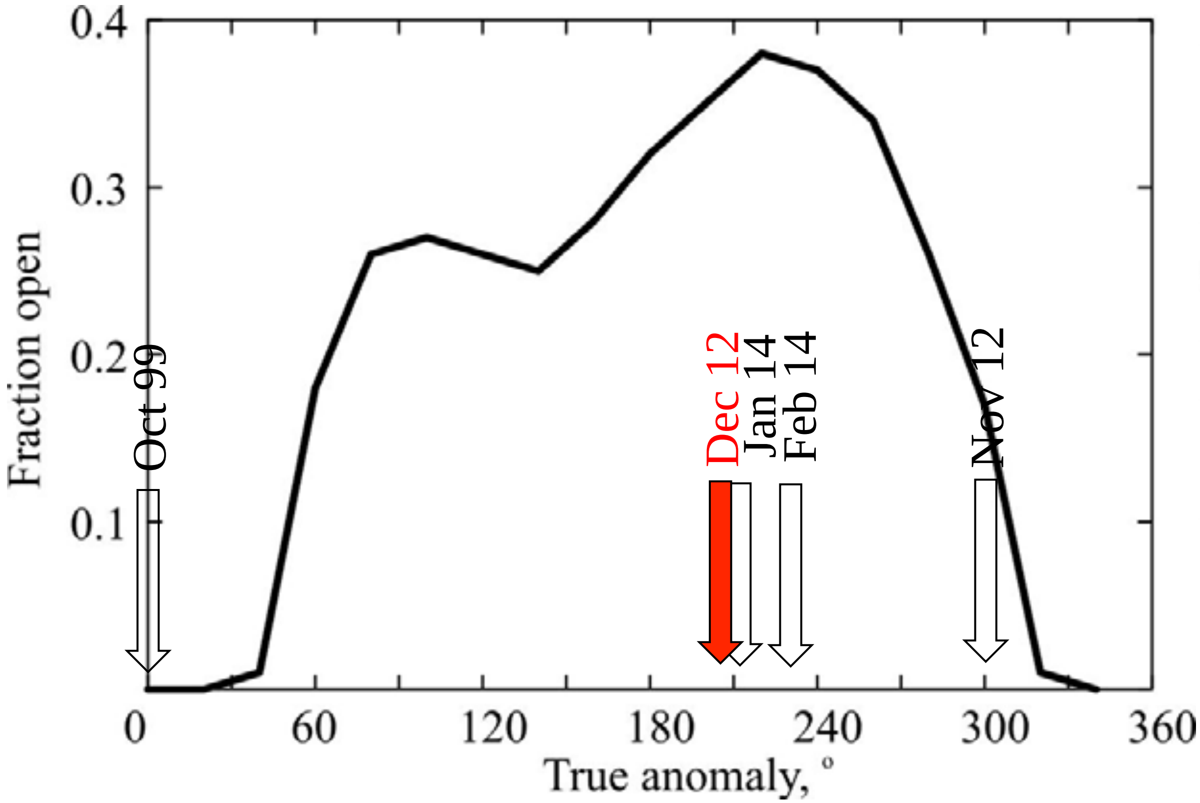
Lessons Learned at Enceladus for Application at Europa : Geophysical Perspectives

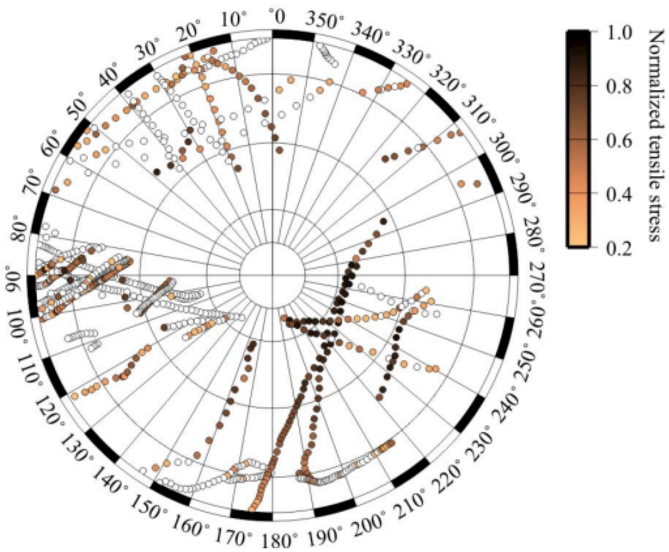
When are fractures open on Europa?



Eccentricity tides (neglects obliquity, forced librations)

Europa polar fractures

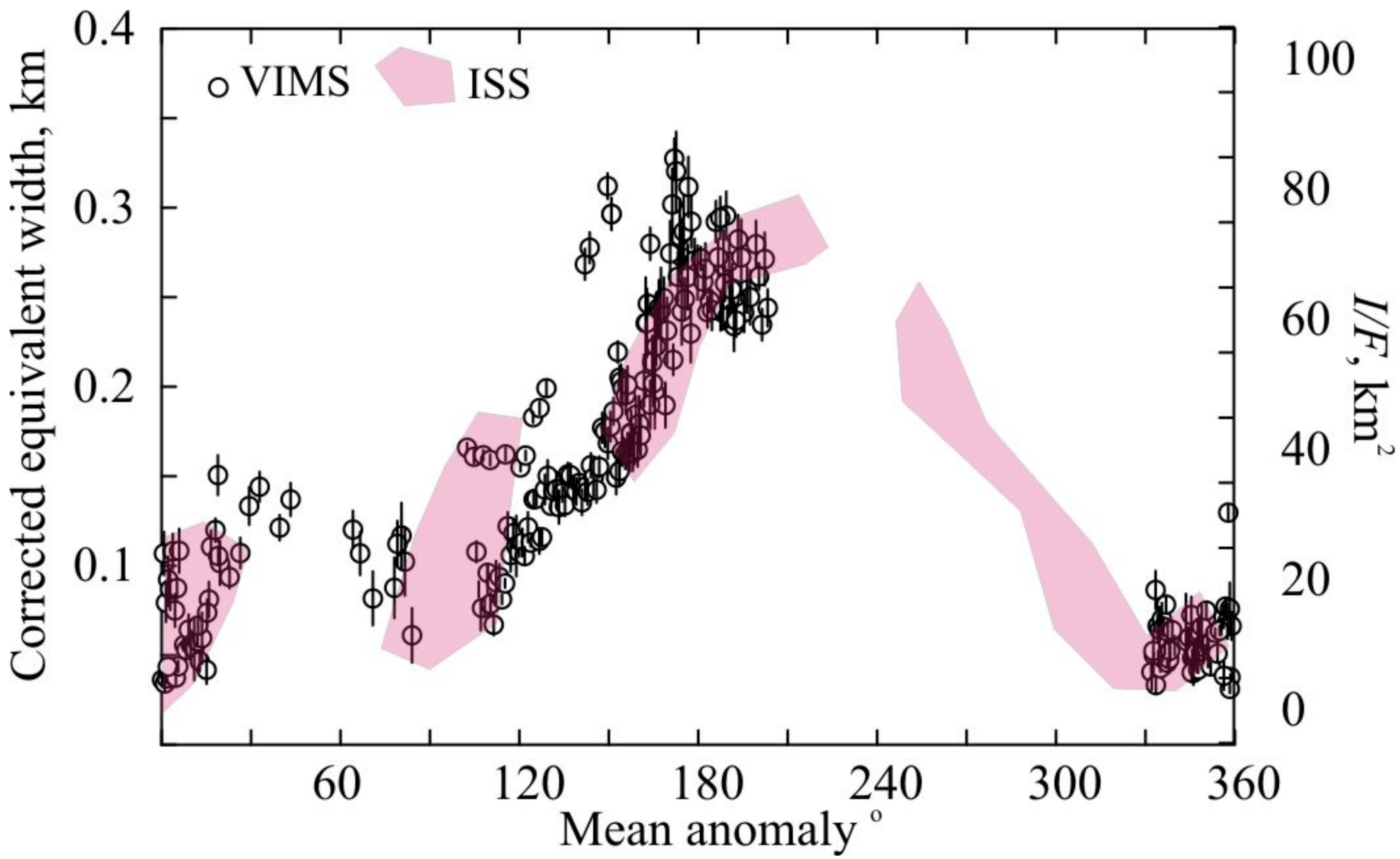




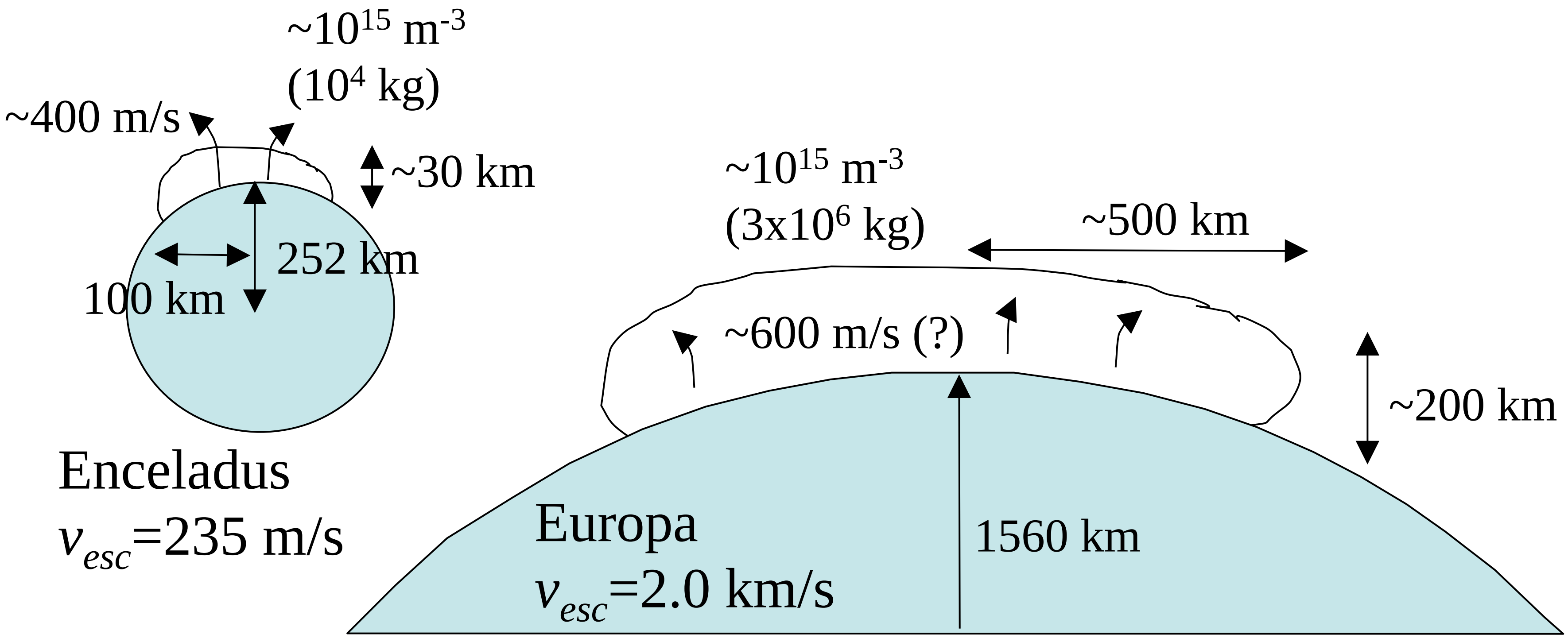
Fractures polewards of 60^{o},
normalized stress > 0.4

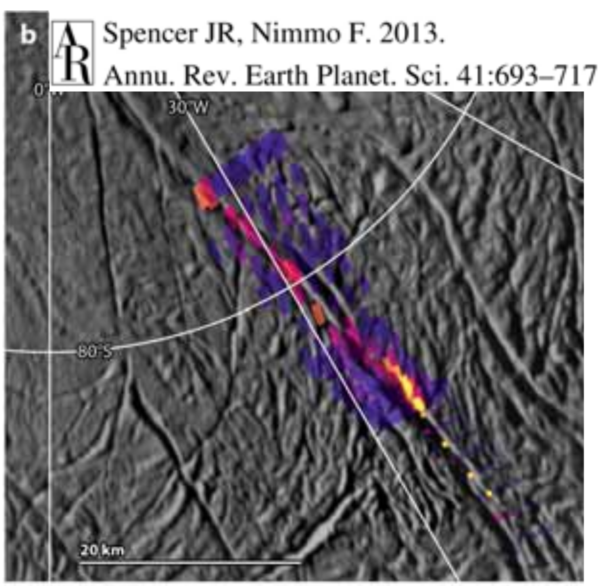
Behavior *not* consistent for same true anomaly
Perhaps infrequent outbursts like Io?

Time Variability at Enceladus



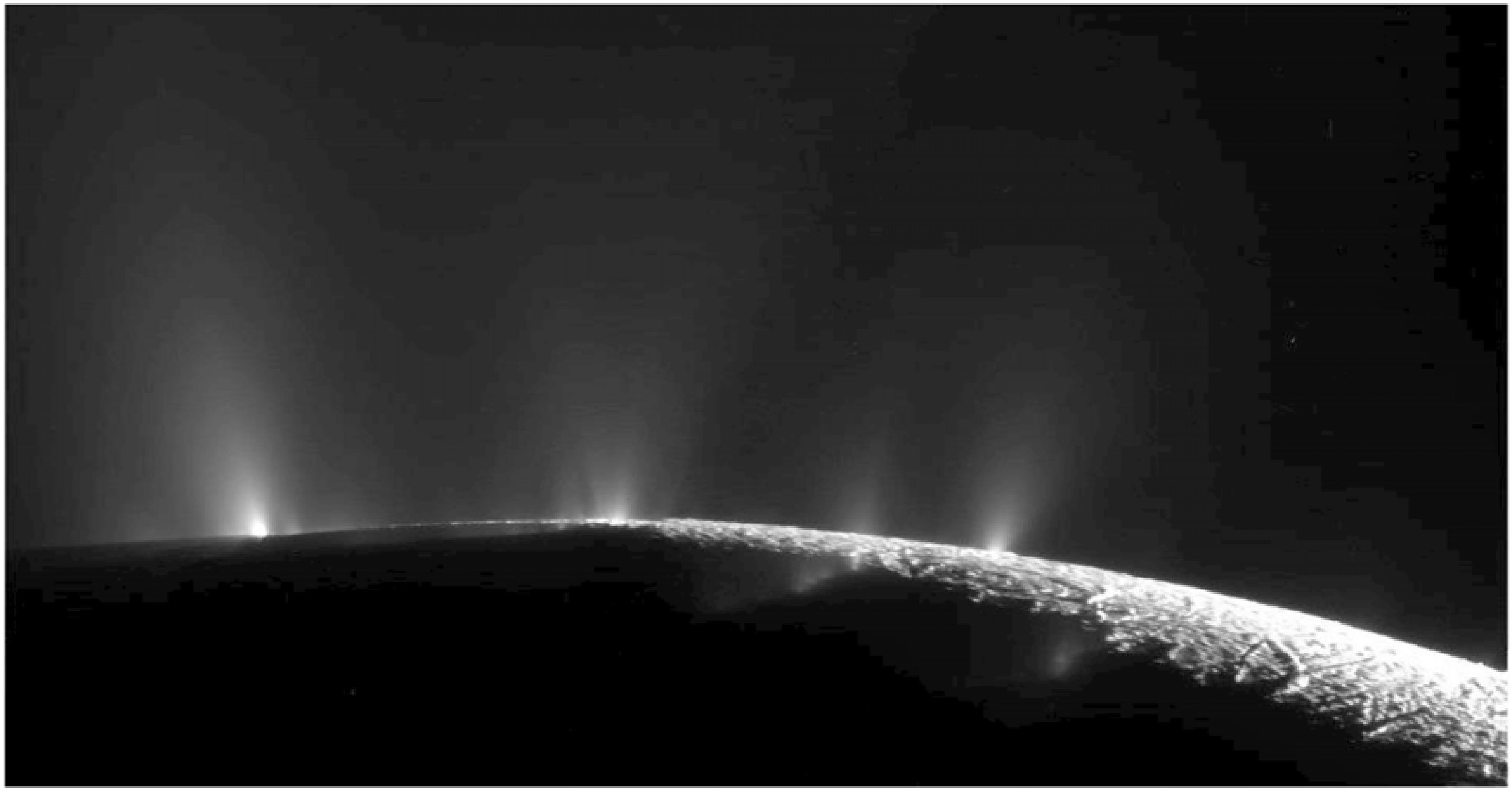
Consistent pattern (+stochastic events?), secular trend?
Broadly consistent with Hurford et al. (2007) model
Details not understood (librations, obliquity, time delay?)





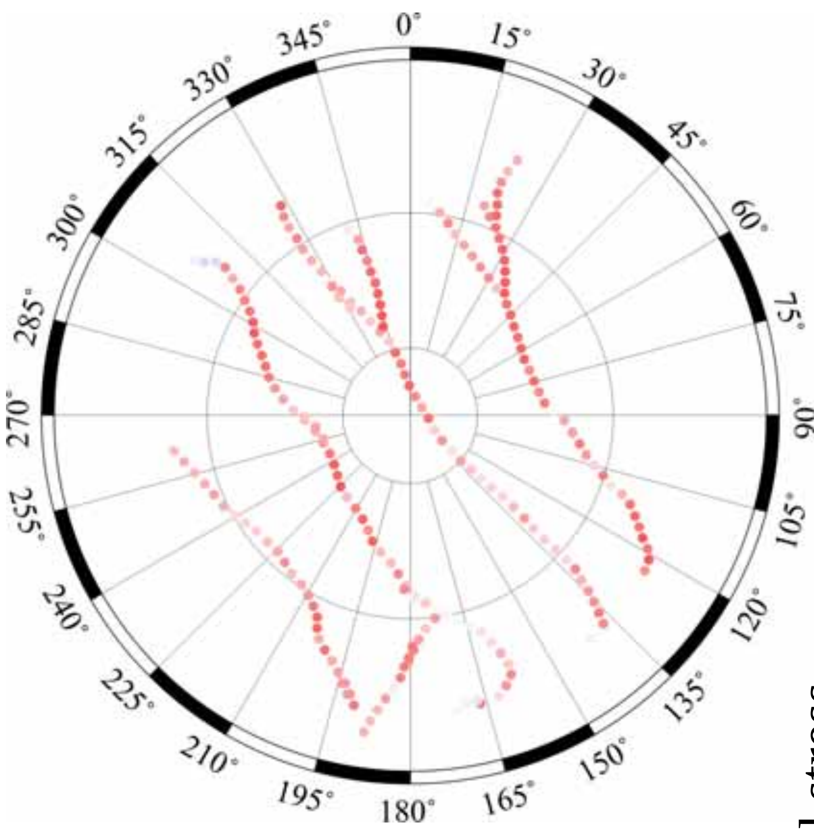
- High inferred vapour velocity implies local high *T* (230 K), ρ
- But number density is low => narrow, warm vents
- Not detectable with PPR (~10^{-2} GW)
- Fallback rate ~ 3000 kg/s (?!)

High Phase Imaging



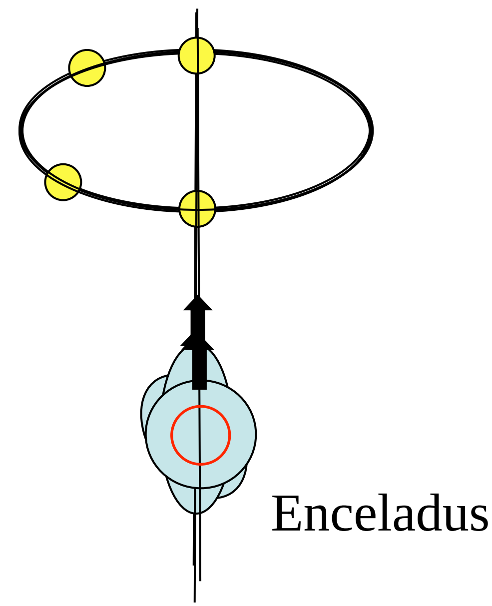
- Forward scattering of light at angles > 135^{o}
- Allows tenuous eruptions to be observed

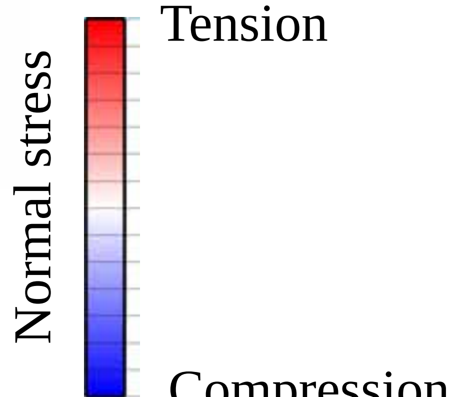
Time-varying stresses



Pericentre
Apocentre
1/4 orbit later

Looking down on the orbit plane





Orbital period 33 hours

PLUME DENSITY AND DYNAMICS MODELS

Summary presentation by William McKinnon
Washington Univ., St. Louis

Intriguing but incomplete evidence for transient “plume” events at Europa:

December 2012 HST (Roth)

Cassini flyby ENA (Westlake)

Galileo E12 (Khurana)

Further observations observations and analysis with HST necessary (Roth, Sparks)

Cassini was true International Flagship, with 12 instruments plus Huygens

“Europa Clipper” is focused flagship, with a smaller instrument complement that still meets the preponderance of Decadal Survey requirements

Woefully premature to turn mission into “Europa Plume Explorer”

Especially true if plumes are real but intermittent on the scale of years (mission could miss them entirely)

Cassini mission was remarkable in that existing instruments could be repurposed to study Enceladus plumes:

CIRS, CDA, INMS, UVIS

So instruments that are flown to Europa should should be designed to encompass this possibility inasmuch as practical. Examples:

UV-capable imaging camera (Schenk)

Long-wavelength thermal imager (Spencer)

Some Higher Order Questions for Plume Models

- How can dynamics models best work together to address the big questions? Can discrepancies be resolved?

- What measurements can we make from "Europa Clipper" in order to understand the dynamics of the (putative) plumes? What do we really need?

- What can mission data contribute to engineering constraints relating to flybys through plumes?

- Can broader science questions be addressed with plume data through modeling (e.g. interior processes)?

Fagents – review of cryovolcanism

Take home: higher gravity may lead to intermittent eruptions on Europa (tidal stress magnitudes for floating ice shells on both bodies are similar), time evolution of gas compositions

Goldstein – detailed DSMC models of volcanic plumes, distinct from impacts

Take home: Io-like patterns expected, presence or absence of top shock depends on gas density and velocity; transient events from small impacts will likely occur

Teolis – gas dynamics models

Take home: volatiles don't just erupt but freeze out, hop, migrate. We should search Europa for cold traps and evidence of prior venting

Mitchell – plume model in development

Take home: "follow the fluid"

Also, understanding plumes (flux of erupting materials, including relative abundances, heat output, direct observation of density structure of plume and response to tides, if any), could contribute significantly to the Ice Shell & Ocean Objective in Traceability Matrix (ocean, shallow subsurface, subsurface-surface interface).

Postberg – application of Enceladus plume model to Europa

Ingersoll – Enceladus plume model (particle velocities from ISS analyses)

Take home: Reconciliation? Particle size distribution will depend on balance of homogeneous and heterogeneous nucleation, geometric conditions at vents (Schmidt model uses distribution of vent geometries, more robust)

Bolton – Microwave emission from plume and exosphere (mm-wave spectroscopy)

Another compositional technique, but not in situ. New for planetary, but promising; Rosetta, JUICE flying one

Astrobiology Presentations

Europa Plume Advisory meeting, session summary
June 3, 2014

Summary prepared by Jeff Kargel

Tim Cassidy– Atmospheres
Chris Glein– Ocean compositions, Enceladus, Earth, Europa
Kevin Hand-- Astrobiology
Ralph Lorenz-- Astrobiology
Jeff Kargel– Europa ocean composition
Steve Vance– Plume/ocean chemistry links, Hydrothermal chemistry and thermohaline layering in Europa's ocean

Jeff Kargel

What are the compositional and process links amongst the ocean, deep rocky interior, seafloor, icy shell, surface, and plume?

How do cation and anion abundances and ratios constrain shell thickness, ocean thickness, ocean pH and Eh, seafloor crust/ocean interaction?

What/if any gases are available to drive plume expulsion?

What processes cause ocean thermohaline stratification, and what processes mix it up?

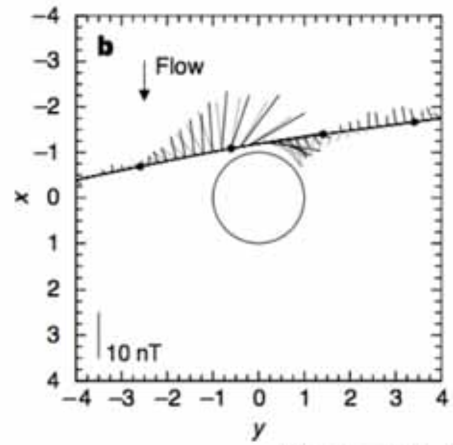
Tim Cassidy

First, why you should care:

The atmosphere/magnetosphere interaction muddles magnetospheric sounding:

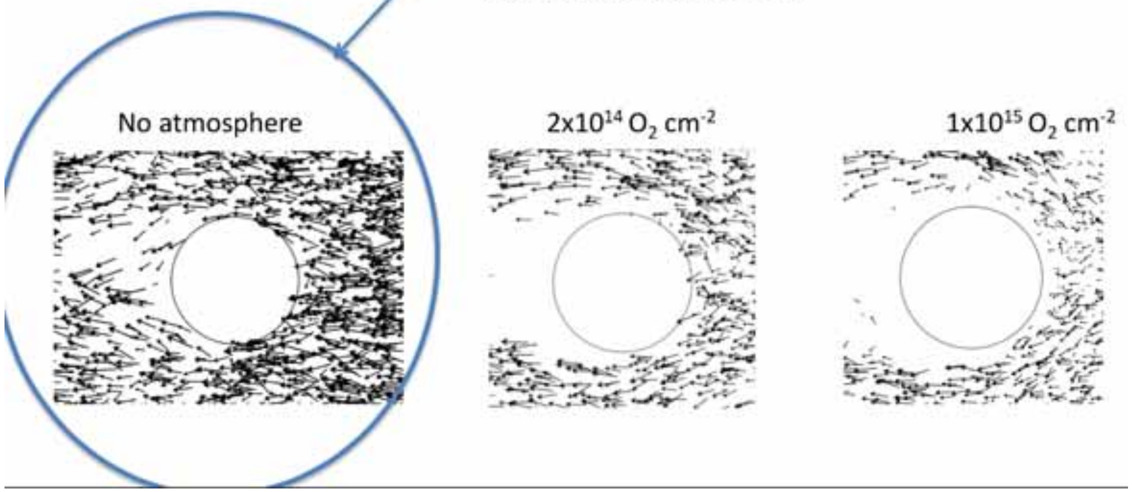
Ideally, people would like to measure induced dipole to the O(1 nT) level, plasma interaction limits ability to measure induced dipole to O(10 nT)

-Frank Crary and collaborators at LASP



Khurana et al., 1998

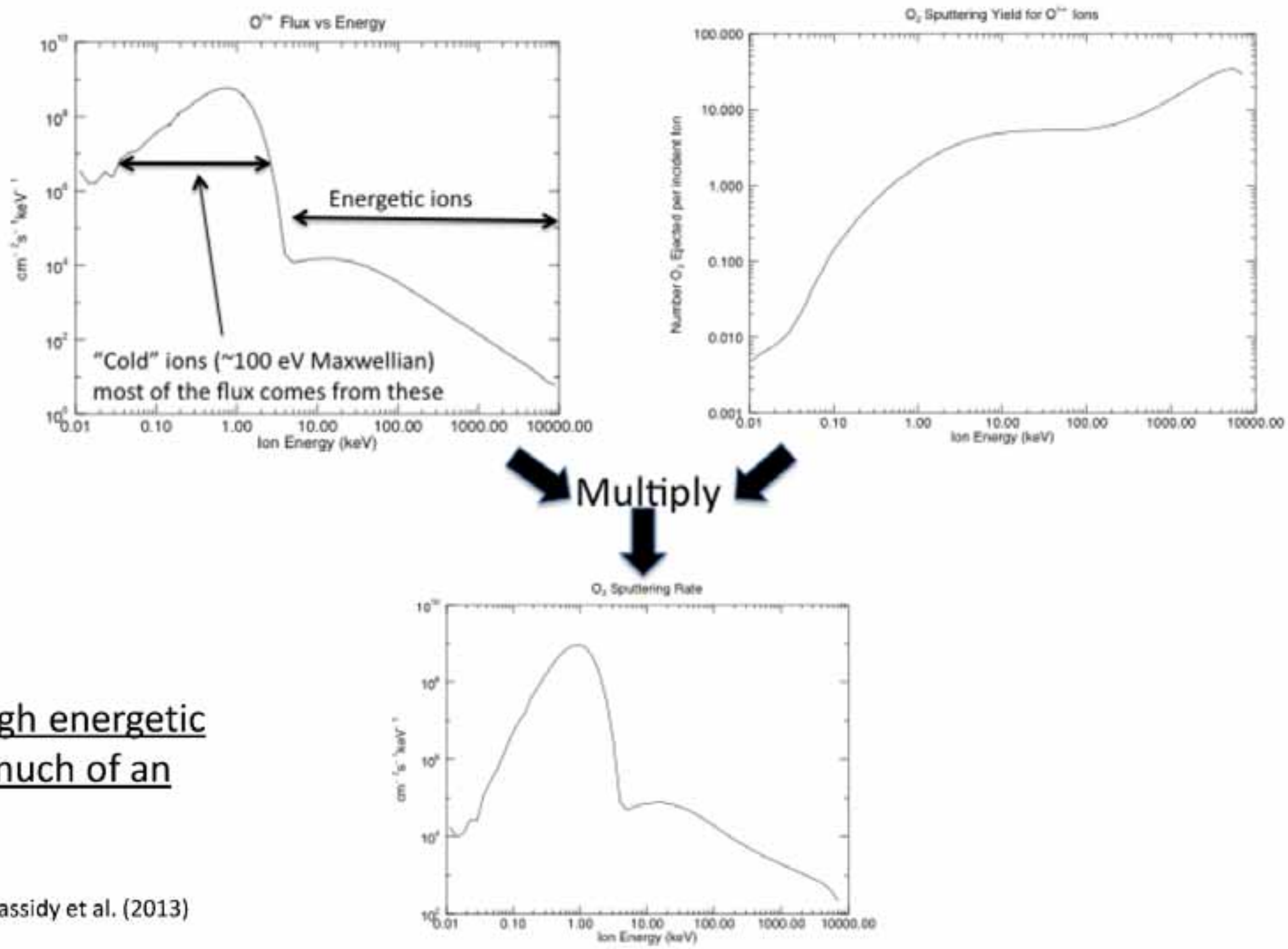
Modelers:
make sure your plasma can hit the surface in the absence of an atmosphere



Tim Cassidy

3 of 3) The O_2 atmosphere is created by 'cold' ions hitting the surface

Sputtering is distinct from what produces Europa's atmosphere—radiolysis followed by sputtering. Cold ions are abundant and effective at creating O_2.



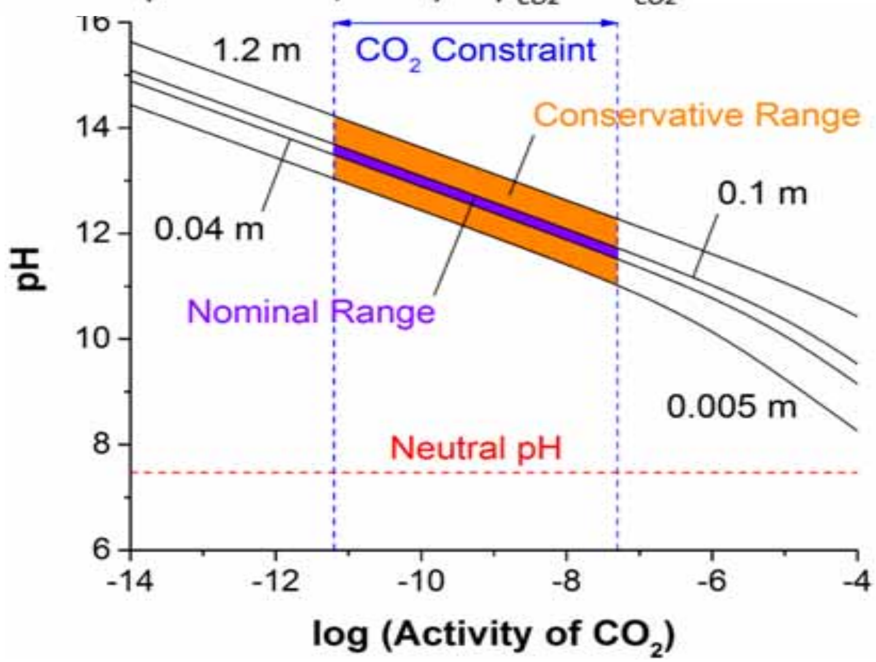
There is not enough energetic ion flux to make much of an atmosphere.

See Teolis et al. (2010) and Cassidy et al. (2013)

Chris Glein

Enceladus ocean Eh-pH modeled from subset of Cassini INMS/SDA plume data:

- The carbonate system as a pH indicator from space:
  - $CO_2 + H_2O \leftrightarrow H^+ + HCO_3^-$
  - $HCO_3^- \leftrightarrow H^+ + CO_3^{-2}$
- Evaluation of the pH requires:
  - Concentration of dissolved inorganic carbon (DIC) = $HCO_3^- + CO_3^{-2}$
  - Thermodynamic activity of CO_2 (a_{CO2})
- On Enceladus, we have estimates of both:
  - Cosmic Dust Analyzer (Postberg et al., 2009) → DIC
  - Ion and Neutral Mass Spectrometer (Waite et al., 2009) → p_{CO2} → a_{CO2}



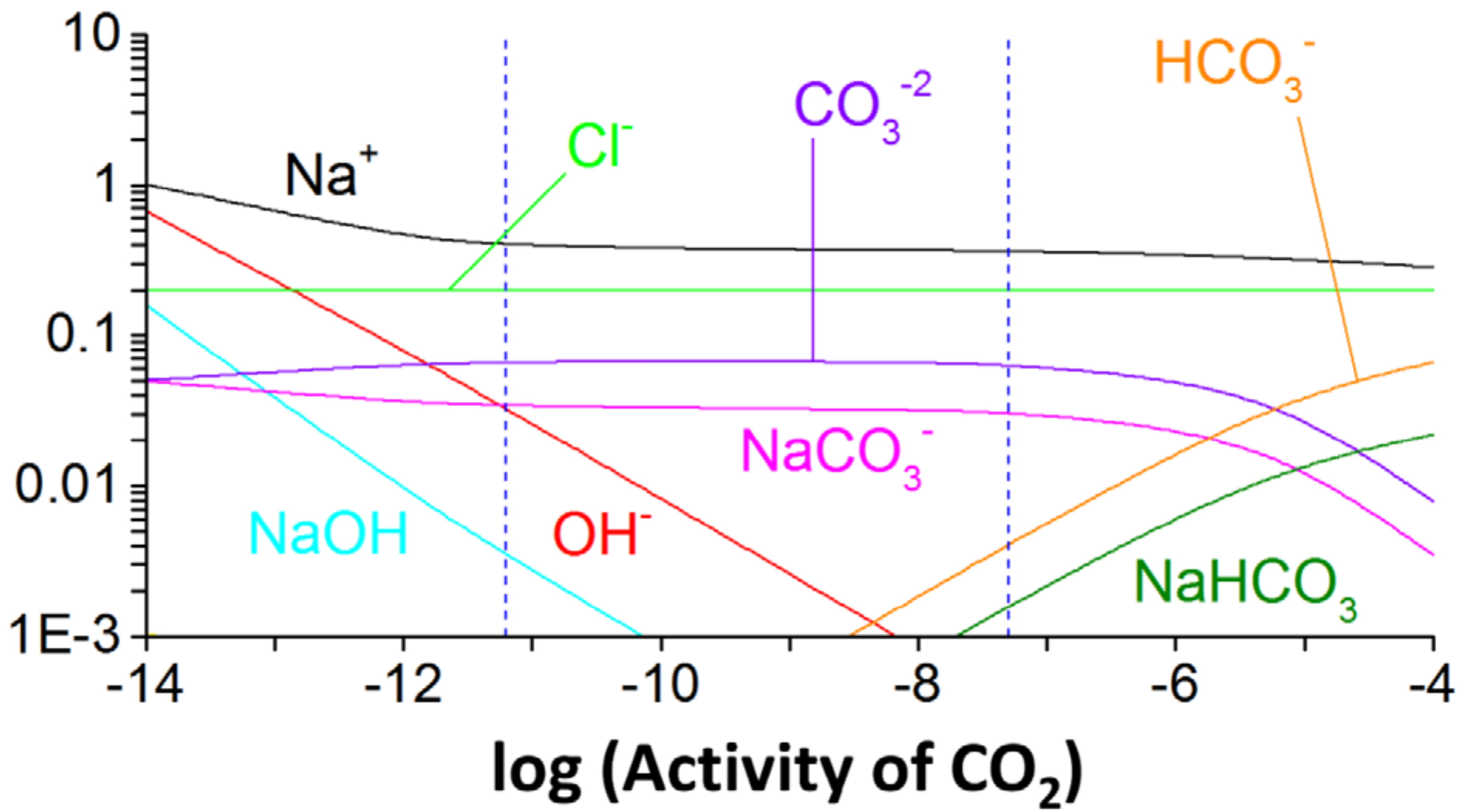
pH provides key information on:

1. Type of rocks on the ocean floor
2. Oxidant delivery
3. Organic speciation (organic acids, amines)
4. Habitability

Chris Glein

Enceladus ocean Eh-pH modeled from subset of Cassini INMS/SDA plume data:

Add Cl^- (from CDA data) and we can get the major speciation



Chris Glein

- Potential indicators of the oxidation state (some gases, others inside plume particles):
  - H_2 (must verify not impact-generated → much lower D/H than in H_2O)
  - Other hydrides (CH_4, NH_3, H_2S)
  - Fe^{+2} (in lower pH ocean)
  - Formate ($HCO_3^- + H_2 \leftrightarrow HCO_2^- + H_2O$)
  - Other organic compounds
  - SO_4^{-2}, NO_3^-, ClO_4^- (very oxidized) – Better method of anion detection than CDA???

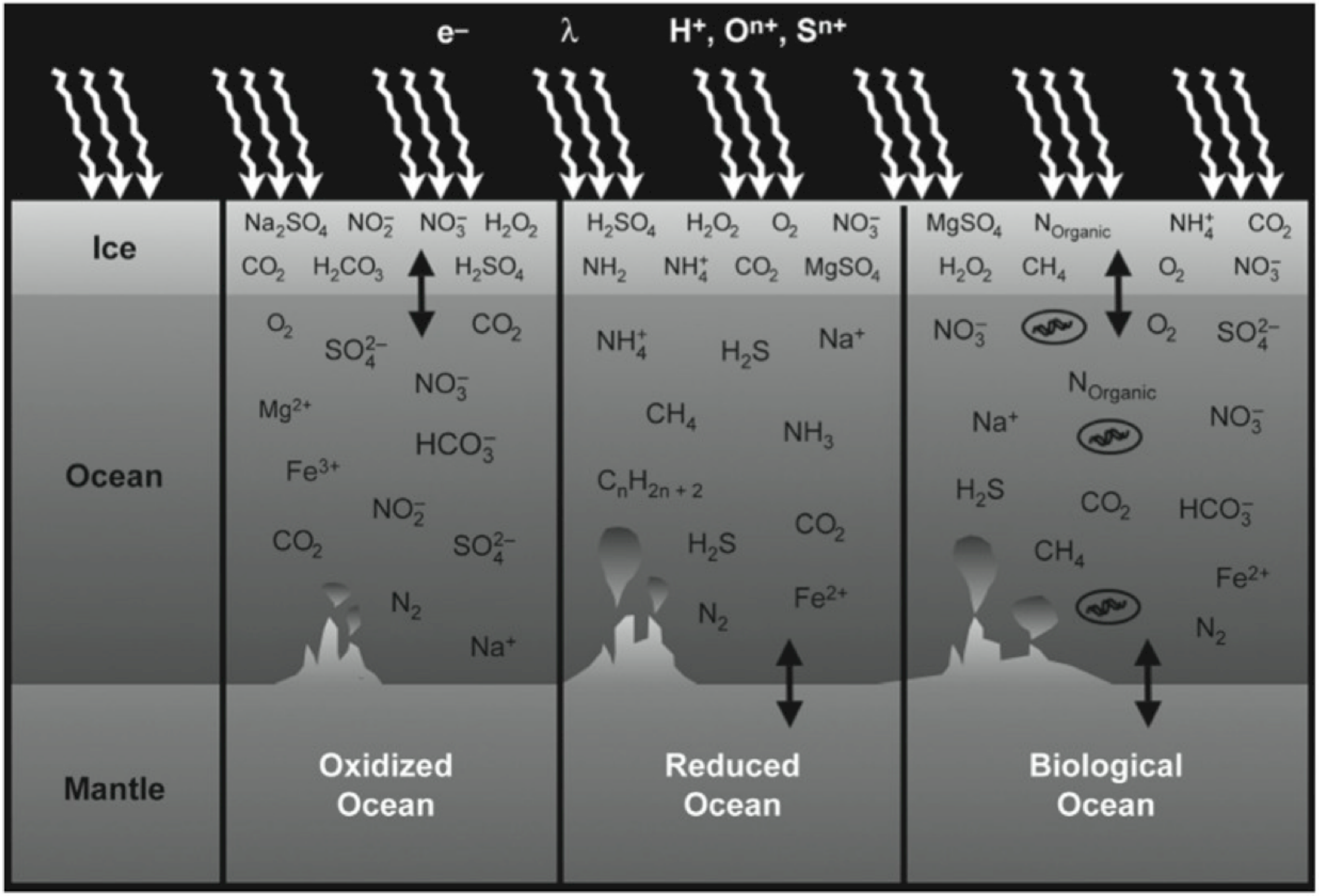
Nature of the Plume Source

- Dry source (e.g., clathrates)
  - Vapor-dominated plume
  - Nonpolar gases (CH_4, CO_2, CO, N_2, Ar)
  - Hydrophobic organics in gas (C≡C, C≡N)
  - D-rich hydrocarbons (if primordial)

- Liquid water source
  - Higher ice/vapor ratio
  - Salts in plume particles (Na^+, Cl^-, CO_3^{-2}, Mg^{+2}, SO_4^{-2})
  - Hydrophilic organics in particles (C=O, O=C-OH)
  - Hydrocarbon D/H similar to H_2O

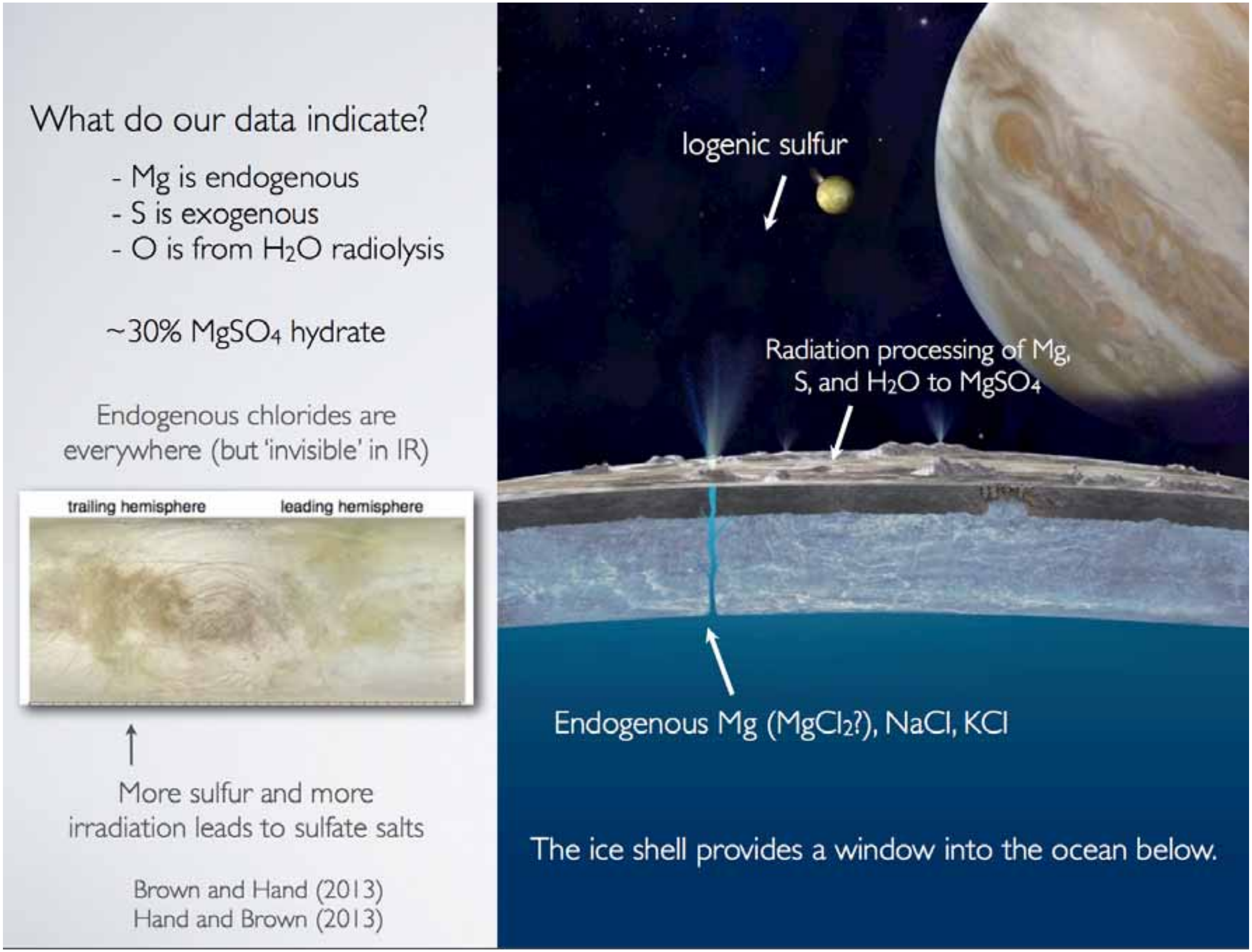
Kevin Hand

Ice Shells as Windows to Ocean Chemistry



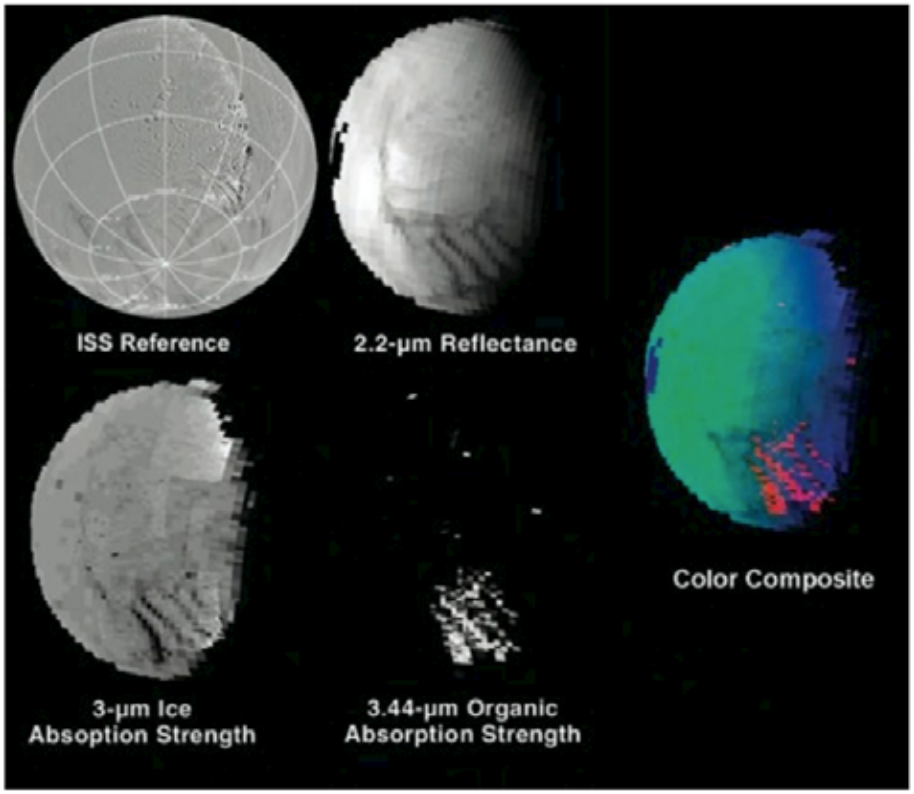
Hand et al. 2009

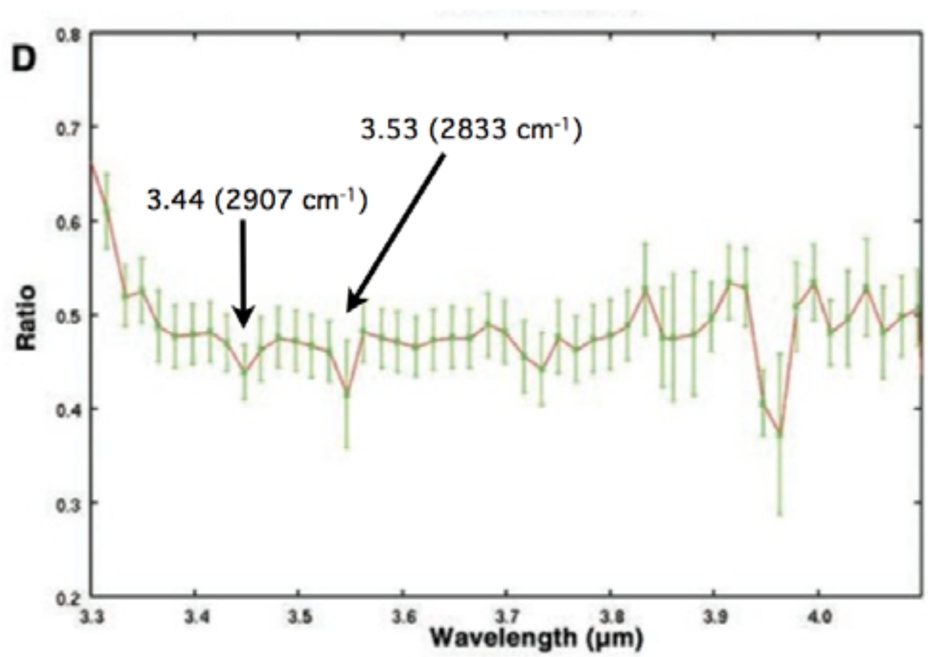
Kevin Hand


What do our data indicate?
- Mg is endogenous
- S is exogenous
- O is from H_2O radiolysis
~30% $MgSO_4$ hydrate
Endogenous chlorides are everywhere (but 'invisible' in IR)
trailing hemisphere
leading hemisphere
More sulfur and more irradiation leads to sulfate salts
Brown and Hand (2013)
Hand and Brown (2013)
Iogenic sulfur
Radiation processing of Mg, S, and H_2O to $MgSO_4$
Endogenous Mg ($MgCl_2$?), NaCl, KCl
The ice shell provides a window into the ocean below.

Kevin Hand

Organics are important chemical constituents of an ocean, important For prebiotic chemistry and life itself. But can we believe some organic detections? We need to do better than Galileo and Cassini when we go Europa.

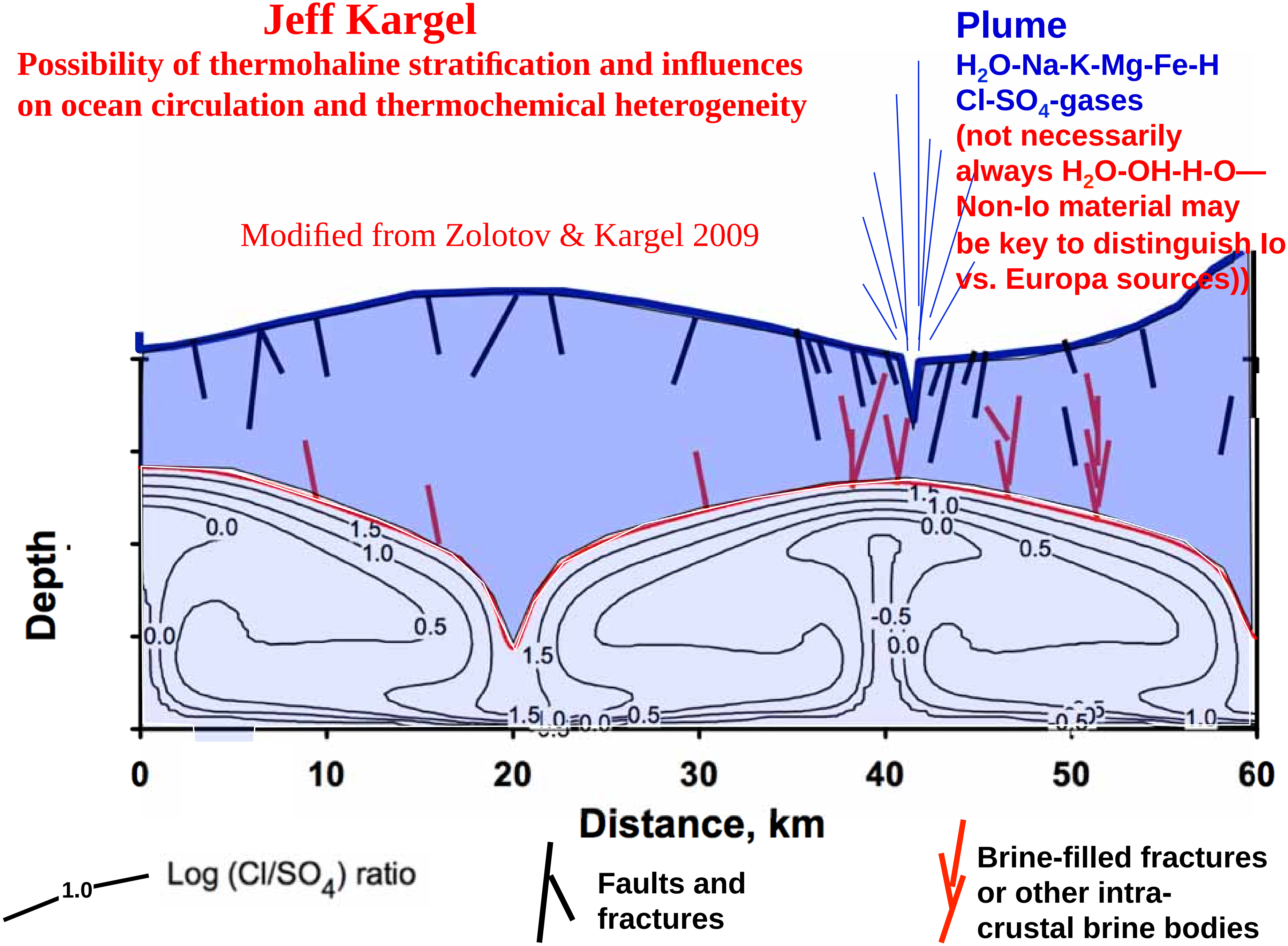




Brown et al. (2006)

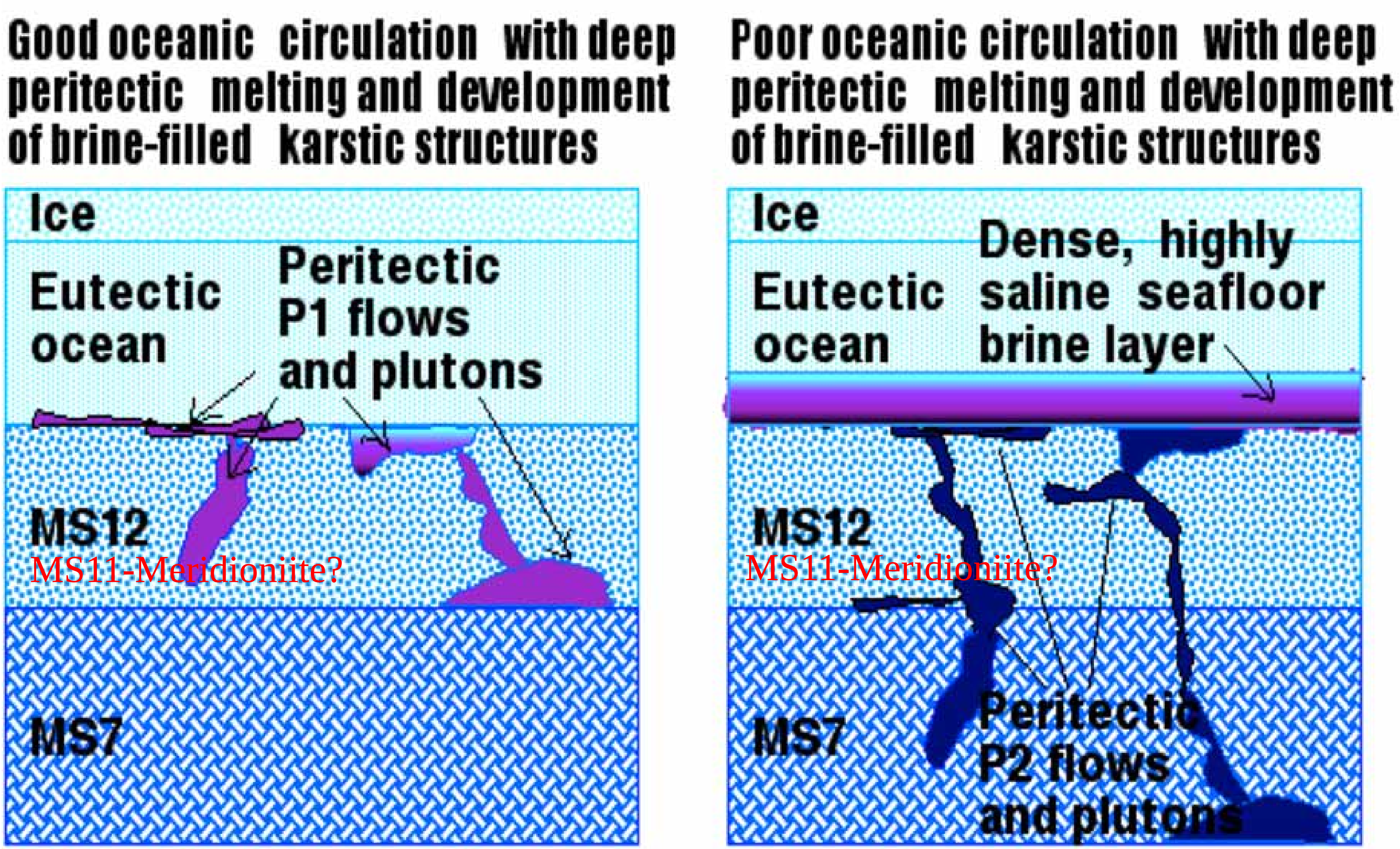
Jeff Kargel

Possibility of thermohaline stratification and influences on ocean circulation and thermochemical heterogeneity



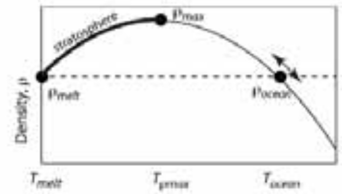
Jeff Kargel

Suboceanic crustal structure may be complex

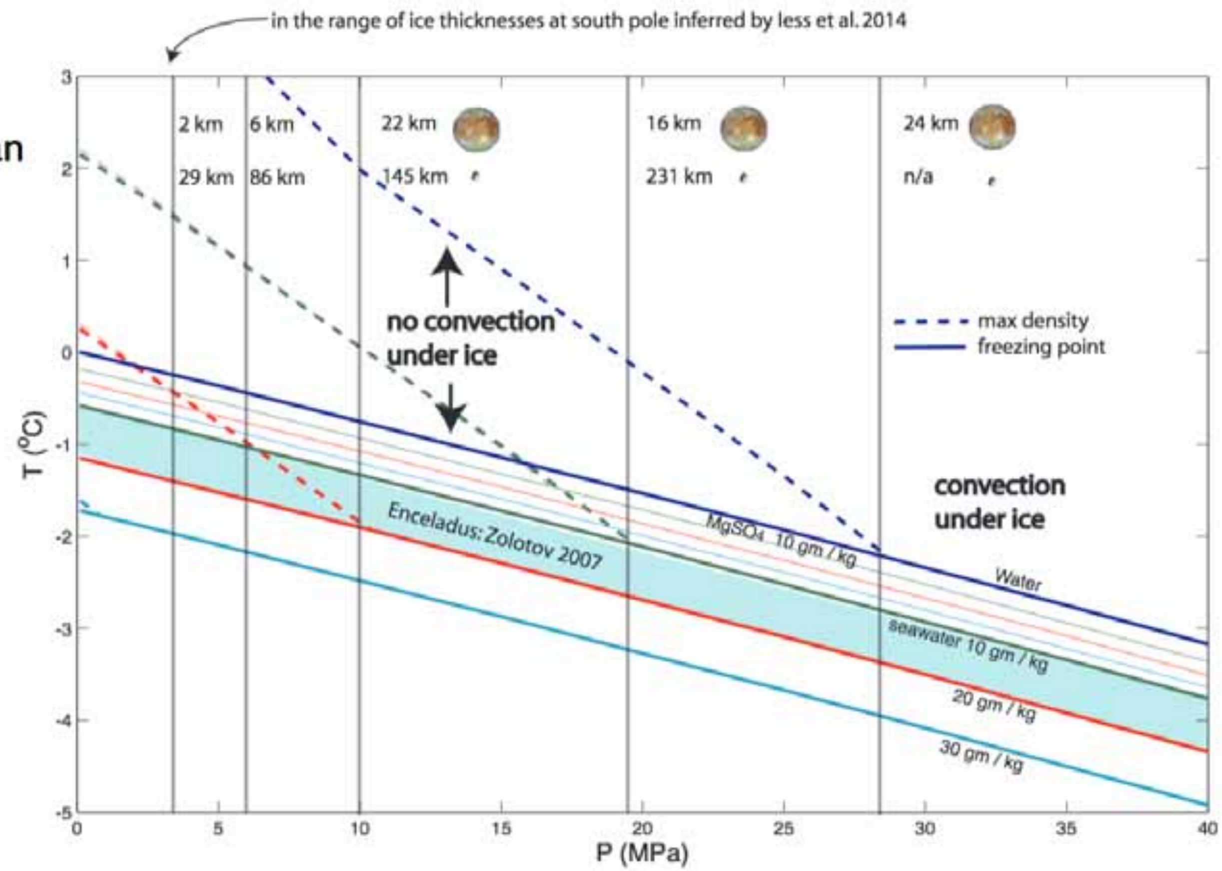


Steve Vance

How does plume composition correlate with ocean composition?



- Ice covered lakes on Earth can be non-convecting where pressure and salinity do not water's anomalous thermal properties.
- Europa has no ocean stratosphere even for freshwater if d_{ice}> 24 km
- Enceladus may not convect anywhere due to lower pressure in its ice.

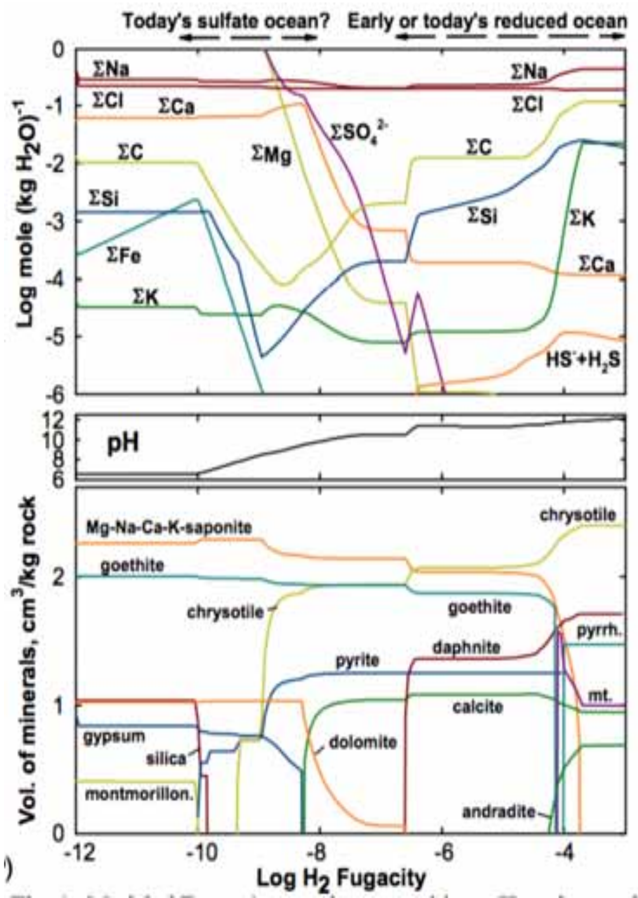


(Modified from Vance and Goodman 2009, after Melosh et al. 2004)

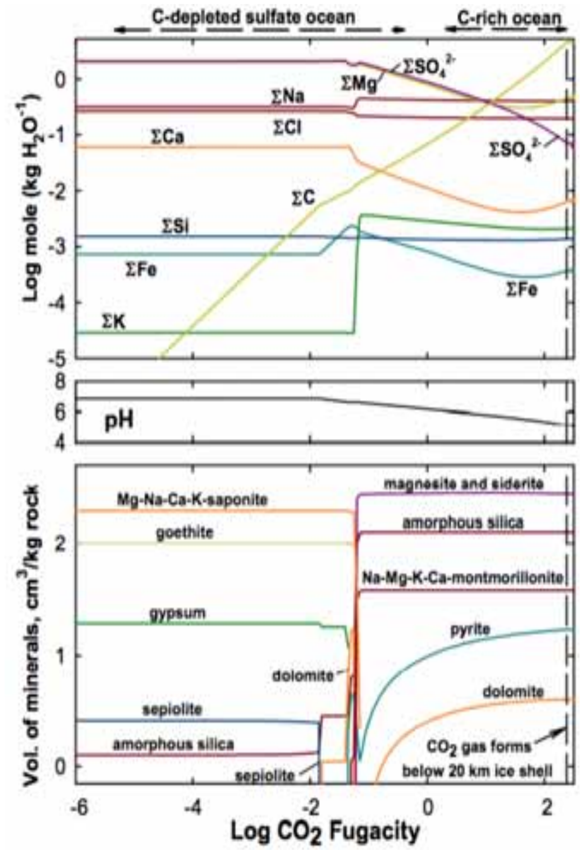
Steve Vance

Summarizing work by Misha Zolotov in Zolotov (2007, 2008, and Zolotov and Kargel 2009)

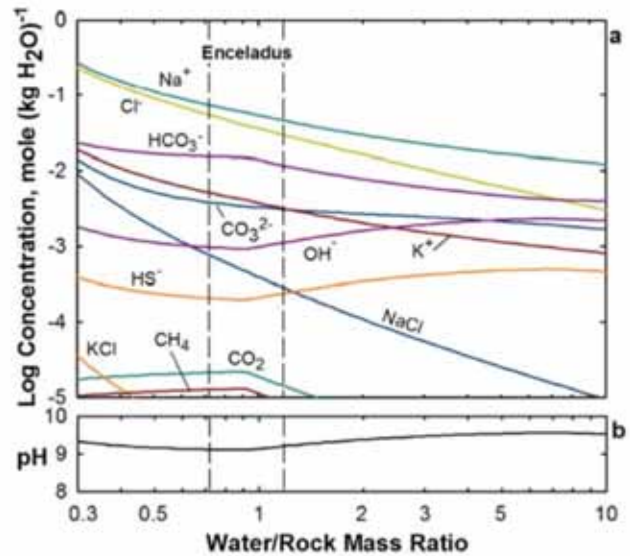
Europa



Europa



Enceladus



ASTROBIOLOGY SESSION HIGHPOINTS/SUMMARY

There seems to be a scientific consensus that the reported Europa plume is an extremely important finding, is compelling but not convincing. What has been reported does not lend itself to making strong predictions about the plume's existence, timing, or locations.

Enceladus appears to be a great or at least popular analog model. Io plumes may have some things to teach us about how to do plume studies. Tenuous atmosphere is important, as it affects the ability of the magnetosphere to alter the surface and thus affect what we see (Cassidy).

Trace species seen on Enceladus's surface (e.g., 3.44 μm feature indicating organics) is weak at best– not a great detection. Require better reflectance spectroscopy (Hand).

Enceladus ocean Eh not well constrained but might be reducing (CH_4 and NH_3) (Glein).

Enceladus ocean pH is likely to be alkaline (pH ~12), buffered by carbonate-bicarbonate (Glein). (Kargel: Close to where free ammonia may exist– maybe (also) buffering by ammonia-ammonium equilibria?

Ocean pH and Eh discriminants identified (Glein, Hand).

Ocean composition, temperature, ice shell thickness are interdependent (Vance, Kargel).

Ocean circulation and thermohaline layering are unknowns (Kargel, Zolotov, Vance).

Suboceanic crustal structure may be complex and is not known, e.g., volcanic rocks vs altered serpentinite mud vs. thick salt beds. (Glein, Hand, Vance, Kargel).

**We all love water-based plumes,
especially if they derive from an ocean, especially if the plumes shoot up small anchovies**

(just not onto my pizza, please).

Beware, stealth plumes may lurk!

Maybe CO or CO_2 or H_2 plumes. They may or may not be linked to an ocean, maybe are linked to clathrates or degassing from other reservoirs and non-ocean processes. (But they would be interesting too.)
(Glein, Kargel)

ASTROBIOLOGY SESSION HIGHPOINTS/SUMMARY/DISCUSSION

We should learn from Cassini's successes (and shortcomings) with Enceladus plumes:

1. **A multi-instrument perspective of the plume is valuable. Improved UV/VIS/NIR/SWIR spectroscopy– must do better than Cassini (i.e., 3.4 μm feature). Neutral/ion mass spectroscopy. Magnetosphere measurements. Microwave probing is super sensitive to water. Thermal imaging. Stand-off imaging (Al McEwen call-in).**
2. **Nimble mission planning/flexibility is needed to take advantage of unexpected finds.**
3. **CAUTION: Rosaly Lopes urged against "fishing expedition" (echoed by several people). This does not mean to**
4. **We need the right balance between promoting and facilitating plume investigations with the right instrument suite, but we should not unravel and re-orient a mission to go after plumes that may or may not exist or which are not at this time predictable in time and space (expect some heat about what instrument suite to fly!).**
5. **Mission safety should consider the possible plumes, but over-conservatism is to be avoided (note Galileo plume fly-through at Io, Cassini plume fly-throughs at Enceladus– they survived-- Lorenz and others).**
6. **Ralph Lorenz (paraphrased and interpreted by Jeff Kargel, so blame me if it's not exactly what he meant): Flying through a Europa plume may give us what we need, and it's what we want to do. This Europa mission (whichever is to be selected) will not be a life detection mission, but a habitability assessment. A useful gedankenexperiment is to imagine the challenge of nailing down Earth's ocean conditions, inorganic chemistry, prebiotic chemistry, and physical chemistry (and life itself) if we had a spaceflight through an imaginary plume of Earth's seawater, as seen from space using Cassini-like observational capabilities; we could do a lot, but there would be some big challenges to learn about Earth what we want to know about Europa.**